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ANALYSIS OF ROAD PRICING, METERING AND THE PRIORITY TREATMENT OF HIGH OCCUPANCY VEHICLES USING SYSTEM DYNAMICS

by

William A. Castillo

Committee Chairman: Donald R. Drew
Civil Engineering

(ABSTRACT)

Transportation Systems Management (TSM) employs various techniques such as road pricing, metering and the priority treatment of high occupancy vehicles (HOVs) in an effort to make more efficient use of existing transportation facilities. Efficiency is improved in terms of moving more people through the facility while simultaneously reducing the number of vehicles using the facility. This report uses a hypothetical toll facility and examines four computer modeling approaches to determine which of the approaches are valid in terms of predicting the behavior of trip makers seeking to use the facility in response to various combinations of TSM techniques. Once an approach has been determined to be valid, seven different combination of TSM techniques, or strategies, are compared to a base strategy to determine what strategy or strategies are most affective in achieving the goals of TSM. The strategies examined include combinations of increasing the toll costs to HOVs and low occupancy vehicles (LOVs) as well as reducing the rate at which LOVs are allowed to proceed through the facility.

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I dedicate this report to my wife, Carol. During the past 15 months in Blacksburg, she has provided me tremendous support and encouragement as well as being very tolerant of my strange schedule and work habits. Thank you, Carol.

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CHAPTER 1 INTRODUCTION

Throughout the industrialized nations of the world, more and more motorists are seeking to use existing highway facilities. As a consequence, highway facilities are becoming more crowded, particularly during the peak periods of demand. The increase in the number of motorists using the facilities adversely impacts the users as well as the surrounding community. The most obvious impacts are experienced by the motorists themselves. As the number of vehicles increases, motorists experience a decreased level of service; slower travel speeds, which in turn results in an increase in travel time, and congestion. Costs increase for motorists as a result of congestion. For example, according to a study by the Texas Transportation Institute, congestion cost drivers almost $25 billion in 29 U.S. cities in 1986. These costs were attributed to traffic delays, wasted fuel and higher insurance premiums. While some impacts of congestion are more readily apparent, other less apparent impacts, such as the increase in pollution and the deterioration of the quality of life in congested areas, must also be considered. In a companion study by the Texas Transportation Institute, 51 percent of the business leaders surveyed in 13 of the cities indicated traffic congestion affected their business. Of those leaders, 88 percent said the impact was negative. In light of these considerations, relieving traffic congestion,

and thus minimizing its impacts, is a priority for transportation planners.

In the past, as congestion worsened, transportation planners responded by increasing highway capacity to accommodate present and future vehicle demand. Increasing highway capacity was accomplished by increasing the number of highway lanes. Construction of altogether new facilities, such as limited access highways, was another method used to increase capacity. These methods worked well with seemingly unlimited funds and an abundance of available land.

Today, however, in an era of limited monetary resources as well as dwindling land availability in large metropolitan areas and increased public opposition, the expansion of existing facilities or the construction of new facilities in an effort to meet demand are not as feasible as they once were. Transportation planners, faced with highway facilities which have reached their capacity in terms of the number of vehicles that can be moved, are now confronted with the challenge of improving the efficiency of existing facilities, squeezing out as much capacity as possible in terms of the number of persons that are moved. Many current areas of research, such as intelligent vehicles and "smart" highways, are investigating the possibilities of integrating new technologies into our vehicles and existing transportation facilities in order to increase their capacity. On the other hand, transportation system management (TSM) techniques focus

on improving the efficiency of transportation facilities.

Rather than focusing on increasing the vehicle capacity of highway facilities, TSM seeks to make more efficient use of existing facilities by moving more people while at the same time seeking to reduce the number of vehicles in operation on those facilities. Transportation system management bridges the fields of transportation planning, transportation engineering and systems engineering. Some of the tactics associated with TSM are demand metering, road pricing, and the priority treatment of high-occupancy vehicles or HOVs.

1.1 Project Purpose and Objective

The purpose of this project and report is twofold and is based on a problem posed by Dr Donald Drew. Using a hypothetical transportation facility as the basis for developing a computer model, this project examined the validity of four different modeling approaches in which various TSM strategies were implemented. In this case, validity simply means how well the different modeling approaches predicted the expected, general response of the facility to the various strategies that were implemented. If an approach was found to be valid as defined above, the approach was then used to analyze the various strategies of demand metering, road pricing, and the priority treatment of HOVs and their impact on the number of people moved as well as the number of vehicles in operation on the facility. The objective of the analysis was to determine which strategy, or

combination of strategies, might be more effective in increasing the number of persons moved while reducing the number of vehicles utilizing the facility.

The concepts of demand metering, road pricing and priority treatment of HOVs need to be defined as they are applied in this report. Demand metering, or simply metering, refers to regulating of the flow of vehicles onto a highway facility. Metering is often used on entrance ramps, where vehicles entering mainline traffic are regulated, usually with a traffic signal, in order to allow more efficient movement of mainline traffic. In this capacity, metering can be used to restrict access to a highway and encourage the use of alternate routes, smooth the demand of oncoming vehicles to prevent pulses in mainline traffic, reduce the likelihood of accidents, and reduce emissions, fuel consumption and vehicle operating costs (1). For this project, a toll facility was used to accomplish metering by varying the rate at which vehicles are allowed to proceed through the toll gates for the purpose of controlling the downstream demand of vehicles.

The concept of road pricing involves allocating a fee to the user for the use of the facility with the idea of reducing overall demand or perhaps recouping the cost of constructing the facility. Road pricing can be implemented in various forms as well, including parking fees and tolls. In this project, road pricing was implemented in the form of the tolls charged with the intended purpose of reducing demand.

High-occupancy vehicles can be given priority treatment in an effort to persuade more trip makers to utilize this mode of travel. Forms of priority treatment afforded HOVs include the preferential treatment of HOVs at traffic control devices, reduced or the elimination of tolls for HOVs, priority ramps on freeways, and dedicated HOV lanes. Again, these policies are aimed at reducing the number of low-occupancy vehicles (LOVs) while increasing the number of persons that are able to utilize the facility. In this project, priority treatment of HOVs is accomplished by employing a dedicated HOV lane in each approach. To further examine the strategy of priority treament for HOVs, the policy of reducing the HOV toll cost verses that levied against LOVs was studied as a means to encourage the use of HOVs.

1.2 Project Overview

Four computer models were constructed representing each of four different approaches and various TSM strategies were implemented within each model. Each model was then examined to ascertain it's validity in response to the strategies. If the model was determined to be a valid representation of the system, then the effects of the strategies were analyzed in an effort to determine which strategy, or combination of strategies, had the greatest impact on increasing the number of people moved while decreasing the number of vehicles which utilize the facility. The project proceeded in four basic steps. The first step was model development which included

the development of the four computer models for each of the approaches. These four models were then analyzed in terms of their sensitivity to different model parameter values in step two. Step three discusses the results and draws conclusions based on the results of step two. Finally, summary remarks and recommendations for further research are presented in the last step.

1.3 The Systems Engineering Approach

As mentioned previously, TSM bridges the fields of transportation planning, transportation engineering and systems engineering. Transportation planning is strategic in scope, focusing on the long-term development and impact of transportation facilities. Transportation engineering is concerned with the application of tools and principles in the design of transportation facilities. Transportation system management seeks to more effectively manage current facilities to overcome short- and intermediate-term problems, applying the tools and principles of transportation engineering within a systems concept. The following is a general discussion of systems engineering and how systems engineering specifically applies to this project.

Systems engineering can be approached from two perspectives. On the one hand, systems engineering can be thought of as the engineering of systems or, in other words, the bringing of systems into being (2). In this light, systems engineering is concerned with the correct

identification of the need and then planning, researching, designing, producing and testing the system to ensure it will meet that need. In addition, this aspect of systems engineering seeks to identify user needs as part of the planning and designing process and make provisions to meet those needs throughout the life of the system. These user needs may include such items as training, maintenance requirements and material support. In short, systems engineering is concerned with a system from the time the need is identified, though it's implementation and use, to system retirement and ultimate disposal.

On the other hand, systems engineering can be thought of as the analysis of systems already in existence with the idea of changing or modifying aspects of the system in order to improve it's performance (2). The modeling of systems in order to study the interaction of various subsystems is an important tool of this approach to systems engineering. This project will use the systems analysis approach of systems engineering in order to analyze the affects of TSM techniques on a highway facility in an effort to improve the performance of the system. In the context of this project, improved performance of the system means increasing the number of persons moved while decreasing the number of vehicles which use the facility.

1.4 Systems Dynamics

Traditionally, large problems have been broken down into

smaller, more manageable problems. Solving the overall problem was then a matter of consolidating the solutions of the various smaller subproblems. As problems have became larger and more complex, involving many different variables from a host of disciplines, the aggregate solution may solve the initial problem but the interaction of solutions often produces unexpected and undesirable side effects, creating one or more problems in other areas.

The systems approach to problem solving, however, attempts to view problems not as subproblems to be solved and their solutions aggregated, but as a problem that is part of a larger problem. This approach recognizes the interaction of numerous variables from various and often unrelated disciplines and attempts to balance a solution in terms of competing objectives (3).

The systems approach is one methodology used to find suitable solutions to today's increasingly complex problems, including those found in the field of transportation. Solutions to many of the problems faced by transportation planners and engineers are often a combination of engineering, political, social and economic factors. Since no one specific solution will satisfy the engineering or political or social or economic goal by itself without adversely affecting one or more of the other factors, the systems approach seeks a solution which will balance the competing objectives. In other words, the solution may not be optimal for any one goal

but it is the best solution for all factors taken as a whole. Transportation systems management recognizes the complex nature of modern transportation problems and seeks to integrate the systems approach to problem solving with the more traditional approach of transportation engineering.

Identifying a balanced solution to a complex problem requires a solution method which allows the investigation of variable interactions and the experimentation of different possible solutions without performing trial and error on the actual system. Representing the problem through the use of a model is such a method and allows investigation and experimentation with less risk, less time, and less money than investigation and experimentation on the real system (3). Models exist in several forms, but an overriding factor of any model is it must capture the real system in sufficient detail to permit investigation of variable interaction and experimentation with alternative solutions.

One form of model used in the systems approach is the computer based simulation model. These models are ideally suited for investigation and experimentation since once the simulation model is built, it can be run repeatedly on a computer, changing the values of the decision variables. This facilitates a thorough understanding of how the system variables interact and permits the identification of a balanced solution.

An aspect of the systems approach to problem solving is

that problems, or systems, do not remain static but are dynamic. That is, problems involve factors or quantities which change over time and they change over time as a result of feedback. Feedback can be thought of as the transmission of information into a system which affects the information returned and thus influences the further transmission of information into the system. This cycle forms a feedback loop which can either be positive, in which the feedback reinforces continued growth or decline of the system, or it can be negative, in which feedback causes the system to seek stability.

Together, feedback theory and simulation models combine to form a systems methodology called systems dynamics. Systems dynamics provides a framework in which to understand large, complex problems. This project implements the systems dynamics methodology in order to gain an understanding and explore the interaction of various TSM policies in an attempt to lesson congestion and improve efficiency on a highway facility. The language used to construct the simulation model is DYNAMO.

DYNAMO is a computer simulation language that derives its name from the words "DYNAmic MOdels." It is intended to model real world systems in order to trace their dynamic behavior over time and was developed in response to Jay W. Forrester's development of the systems dynamics approach to solving complex problems involving feedback. Systems dynamics and

DYNAMO utilize the concepts of levels and rates in order to model systems. Levels can be thought of as an accumulation within a system and can be either tangible, such as an inventory level, or intangible such as a measurement of quality. Rates represent the flow of what is accumulated from one area to another and cause or control changes to levels. Decision rules, called policies by Forrester, control rates of flow and DYNAMO affords the opportunity to experiment with different decision rules and examine their impact on the system under study.

CHAPTER 2 MODEL DEVELOPMENT

As discussed previously, this project will proceed in four basic steps. The elements included in the model development step are the description of the model scenario, a verbal description of the system to be studied, translating the verbal description into a general model which is then expanded to incorporate four different modeling approaches, and finally, model verification. Step one will be addressed in this chapter and will begin with a description of the model scenario.

2.1 Model Scenario

One important aspect of the model building process is to establish the boundaries of the system which is to be modeled and studied. Boundaries are a necessity since if boundaries were not established, it is probable the model could be expanded to such a point that it is no longer manageable and the interaction of the variables under study is obscured. They are established so as to include all factors and physical aspects which relate directly to the system that is to be studied. Those aspects which do not relate directly to the system are considered outside the boundaries of the model and are not included. Understanding the system that will be studied and establishing system boundaries are therefore essential elements of model building.

The models for this project were developed to study how

various strategies of metering, road pricing, and the priority treatment of HOVs impact the number of people that can be moved on a facility as well as the number of vehicles that use the facility. Each model includes some major factors that have a direct bearing on a driver's choice to utilize HOVs, such as the total time (wait time and travel time) required for the trip and the cost (the cost of time and the cost of tolls) incurred in order to make the trip. As such, the boundaries of this model do not include any political or social factors that may impact the implementation of various strategies.

Figure 1 illustrates the model's physical characteristics. The model depicts a 15 mile, four lane (in each direction) facility with a lane capacity of 2100 vehicles per lane per hour. (Only one side of the facility will be modeled.) One lane of the facility is dedicated to HOVs. There are two toll gates per lane with a service rate limited to one half of the lane capacity or 1050 vehicles per gate per hour. The free speed for the facility is 70 miles per hour and the peak hour demand is 10,500 person-trips per hour.

2.2 General Model

The general model was developed in order to provide a framework which then could be easily modified to include various modeling approaches. The general model is first described verbally and then translated into a causal diagram. Although no actual computer model was developed from the

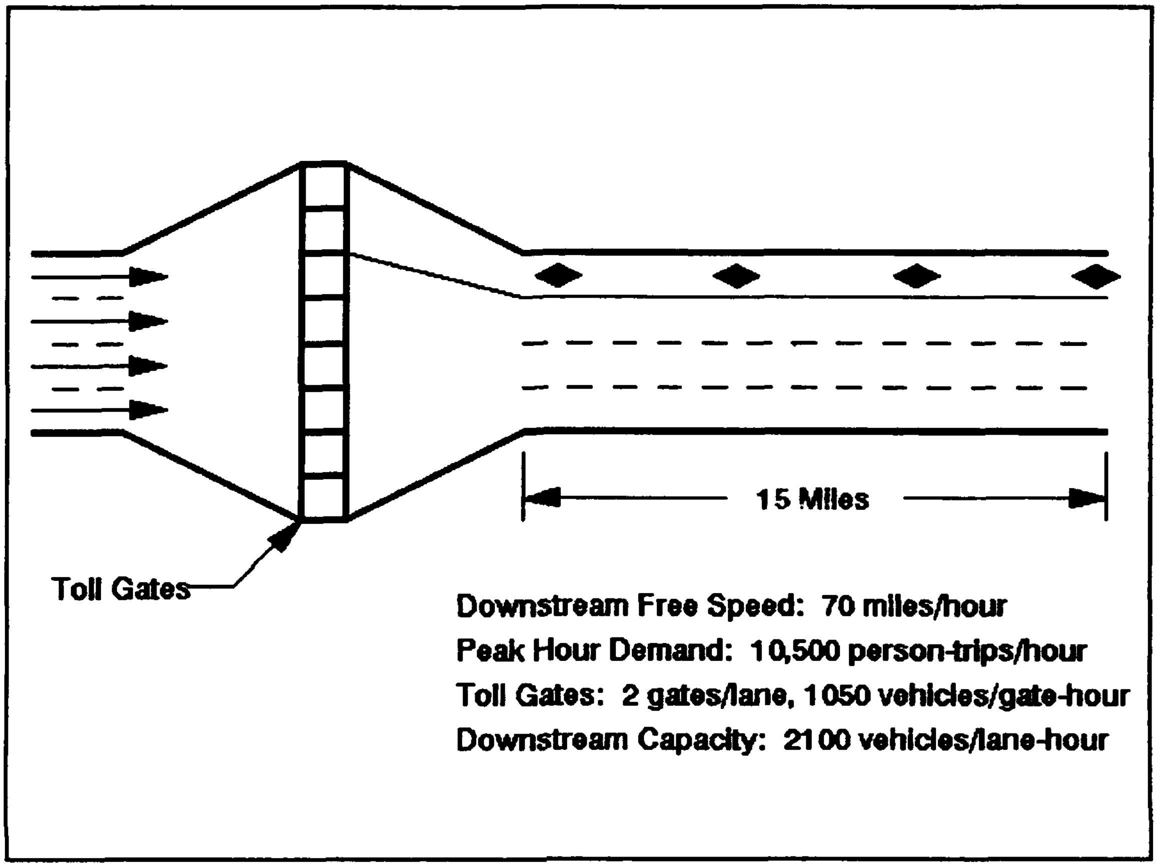

Figure 1 - Highway Facility

causal diagram, an outline of the DYNAMO program was developed to serve as a starting point to implement the different approaches.

2.1.1 Verbal Description

This project will model a toll road facility where peak hour demand exceeds the capacity of the facility, resulting in increased trip time and an increase in costs to the travelers due to congestion. Trip time may include the time spent in a queue at the toll facility in order to pay the toll and the time it takes to actually make the trip. The cost component

for this model is comprised of the cost of time and the cost of making the trip as a result of any tolls assessed.

Initially, for a given demand, a certain number of trip makers will see HOVs as a means to reduce their trip time and cost and therefore, they will choose HOVs as their mode of travel rather than LOVs. This choice will be based on reduced waiting time at the toll facility and a decrease in their travel time as a result of the lower demand on the dedicated HOV lane. As the fraction of trip makers that use HOVs increase, the number of LOVs will decrease which in turn will decrease the travel time and associated costs for LOV trip makers. However, as HOV trip makers increase in number, the costs associated with this mode of travel will increase. Eventually, an equilibrium will be reached in which the perceived benefit of one mode over the over will be negligible and there will be no further increase in the number of HOV trip makers and likewise, no further reduction in the number of LOV trip makers.

2.1.2 Causal Diagram

Systems dynamics uses causal diagrams to depict the relationships that exist between variables in a feedback system. Causal diagrams consist of links, representing relationships, between variables in the system under study. A positive link, or relationship, between variables is represented by an arrow with a plus (+) sign at the head of the arrow. This positive link is interpreted to mean a change

in the variable at the tail of the arrow causes a change in the same direction in the variable at the head of the arrow. Negative relationships between variables are represented by an arrow with a minus (-) sign at the head of the arrow. In this case, a change in the variable at the tail of the arrow causes a change in the variable at the head of the arrow in the opposite direction.

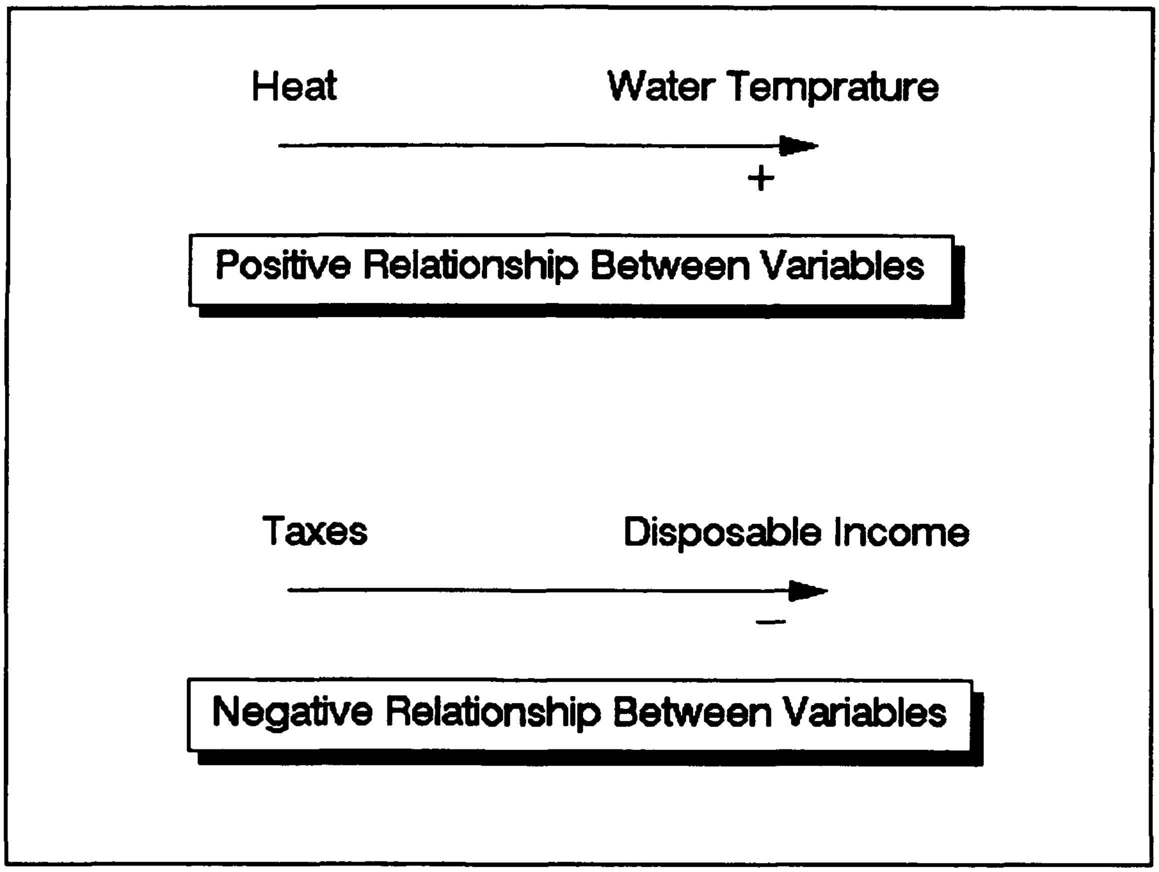

Figure 2 - Variable Relationships

Consider the relationships that exist between the variables depicted in Figure 2. If heat is applied to water, the water temperature will increase. Conversely, if heat is

reduced or taken away altogether, the temperature of the water will decrease. This example points out a positive relationship between two variables in that a change in one variable changes the other in the same direction. Taxes have a negative relationship on disposable income. As taxes are increased, there is less disposable income and as taxes are decreased, disposable income increases. A change in one variable results in a change in the opposite direction for negatively related variables.

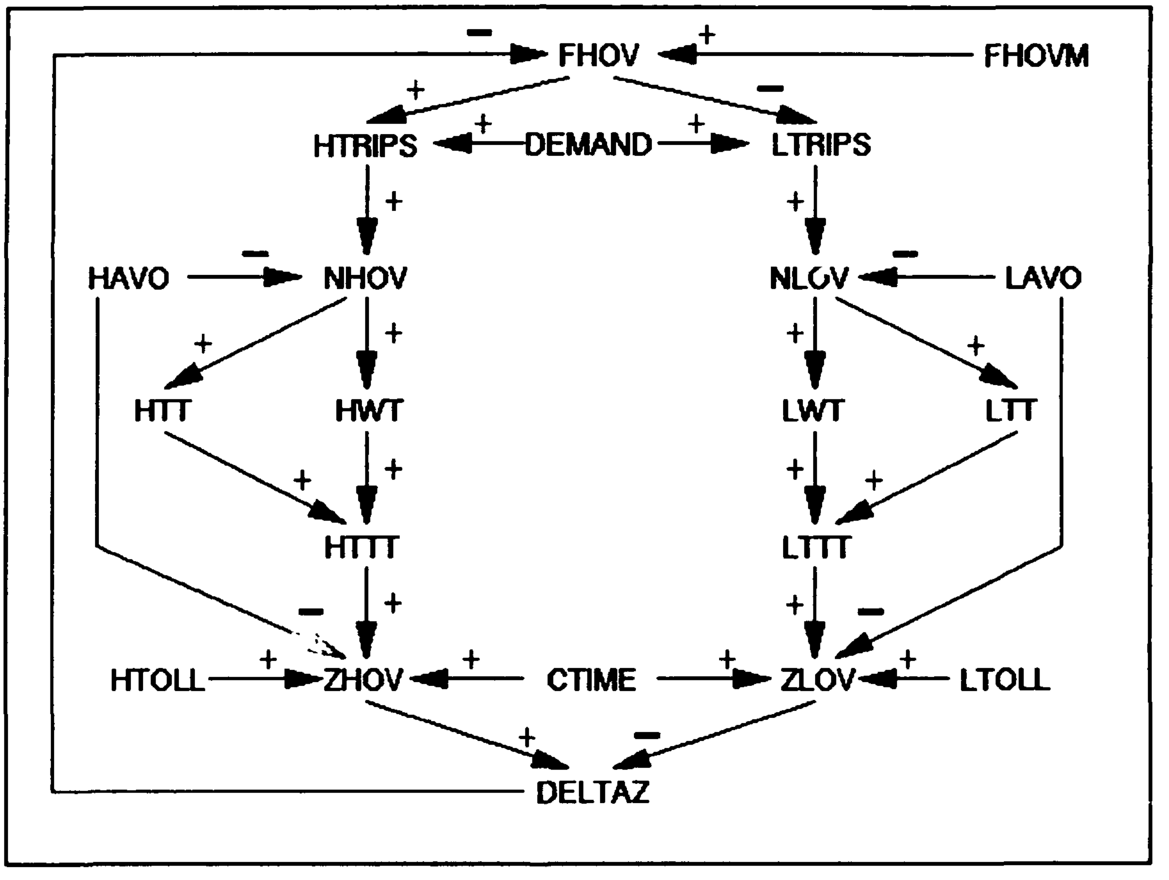

Figure 3 - Causal Diagram

The causal diagram for the general model is depicted in

Figure 3. The fraction of total trips that are HOV (FHOV), limited by the maximum value for the fraction of total trip makers that are HOV (FHOVM), together with demand (DEMAND) determine the number of HOV trip makers (HTRIPS). The remaining trip makers are LOV trip makers (LTRIPS). The average vehicle occupancy for HOVs (HAVO) as well as HTRIPS combine to determine the number of HOVs (NHOV) utilizing the facility. The time an HOV has to wait (HWT) at the toll facility as well as the time it takes to travel through the system (HTT) are both determined by the number of HOVs and combine to make up the total trip time for HOVs (HTTT). Finally, HTTT combines with the toll cost for HOVs (HTOLL), HAVO and the cost of time (CTIME) to determine the disutility for HOV trip makers (ZHOV). A similar relationship exists between the variables describing LOV trip makers. Closing the loop, the difference between the disutility experienced by HOV trip makers and LOV trip makers (DELTAZ) impacts the fraction of the total person-trips that will be HOV trip makers. The cycle will continue until there is no further increase or decrease in the fraction of total trips that are HOV trip makers.

As mentioned previously, the general model was developed in order to provide a framework which would be modified to incorporate the different modeling approaches. Models for four approaches were developed based on the causal diagram of the general model. The various approaches were substituted

into the general model as appropriate.

2.3 Modeling Approaches

In order to evaluate different modeling approaches to the same situation, four different models were developed. The four approaches are briefly described in the following paragraphs.

It was assumed in Approach 1 that wait time at the toll facility was not a factor in determining how many trip makers will use HOVs. As such, wait time was assumed to be zero and was not taken into consideration. The only time element considered in Approach 1 was travel time. Travel time was calculated based on travel speed, which was determined from the volume of vehicles using the facility and the relationship that exists between speed and volume.

In Approach 2, wait time for the trip makers was again disregarded. However, in this approach, a demand-capacity ratio model was used to determine travel time.

For Approach 3, wait time was assumed to be a factor and the average wait time per vehicle at the toll facility was estimated using a cumulative demand and cumulative capacity deterministic queuing model. The speed-volume relationship was again used to determine travel speed, which was then used to calculate travel time.

Finally, in Approach 4, an enhanced cumulative demand and capacity deterministic queuing model was used to determine the average wait time per vehicle at the toll facility. Once

again, the speed-volume relationship was used to determine travel time. Table A summarizes the methods used to calculate wait time and travel time for the various approaches.

2.3.1 Basic DYNAMO Model

Although each approach employs combinations of different methods of determining wait time and travel time, certain aspects of each approach remained constant throughout all four approaches. As such, the basic DYNAMO program remained the

Table A - Modeling Approach Summary

Modeling Approach	Wait Time	Travel Time
Approach 1	Not Considered	Speed-Volume Model
Approach 2	Not Considered	Demand-Capacity Ratio Model
Approach 3	Cumulative Demand/Capacity Queuing Model	Speed-Volume Model
Approach 4	Enhanced Cumulative Demand/Capacity Queuing Model	Speed-Volume Model

same and is discussed here to preclude repetition in the discussion of each individual approach. Reference Appendix A, Basic DYNAMO Program, for the following discussion. Keep in mind, the Basic DYNAMO Program serves only as an outline to incorporate the four approaches. As such, this program is not

complete but it does provide a starting point in which to implement the four approaches.

There were a number of DYNAMO variables which remained unchanged and appear in one or more of the approaches. These variables were labeled system variables in the DYNAMO program. System variables included the peak hour demand (DEMAND) of 10,500 person-trips per hour, the duration of excess demand (DUR) of one hour, downstream free speed (DFSPD) of 70 miles per hour, a downstream capacity (DCAP) of 2100 vehicles per lane-hour, and a jam density (JAMK) of 120 vehicles per lane-mile. In addition, the number of HOV and LOV lanes (HLANES and LLANES) set at 1 and 3 lanes respectively. The length of the facility (LEN) is 15 miles and the cost of time (CTIME) is equal to 8 dollars per hour. The average vehicle occupancy for HOVs and LOVs (HAVO and LAVO) was set at 3 and 1 persons per vehicle respectively. A factor to establish the maximum fraction of total person-trips that can be made by HOV (FHOVM) was set at .4. This factor is used in the modal split model to determine the fraction trips that are HOV trips (FHOV).

The remaining variables are called decision variables since these are the variables which will be altered as various policies are studied. Decision variables include the cost of the toll for HOVs and LOVs (HTOLL and LTOLL) and the service rate at the toll gates for the HOV and LOV lanes (HMU and LMU). Although the toll gate service rate for HOVs is listed as a decision variable, it was kept at a value equal to one

half of the downstream lane capacity in every case. No values are included for these variables in the basic model since they will be modified (except HMU) according to the strategy implemented.

The program flow is fairly straight forward and parallels the causal diagram. It is in the HOV and LOV wait time segments of the basic program that various methods of determining wait time will be inserted. Likewise, in the travel time segments for HOVs and LOVs of the basic program, statements for the two methods of calculating travel time will be inserted.

The final two segments of the model are used to determine the proportion of total trip makers that use either HOVs or LOVs. In other words, this portion of the model splits trip makers between the two competing modes of travel. The process of splitting trip makers between modes is called modal split or modal split analysis. Modal split models can be developed from observation or they can be described by various mathematical equations which are defined in terms of the disutility experienced by the trip makers (1). Disutility is generally defined as a function of the costs, either tangible or intangible, associated with choosing a specific mode of travel. Examples of costs that may be considered are the travel time cost, the cost of time spent waiting, the cost of fares or tolls, costs associated with operating an automobile and the cost of making transfers when public transportation is

considered. In addition, intangible cost factors include such items as the loss of privacy and convenience may also be included in the disutility function.

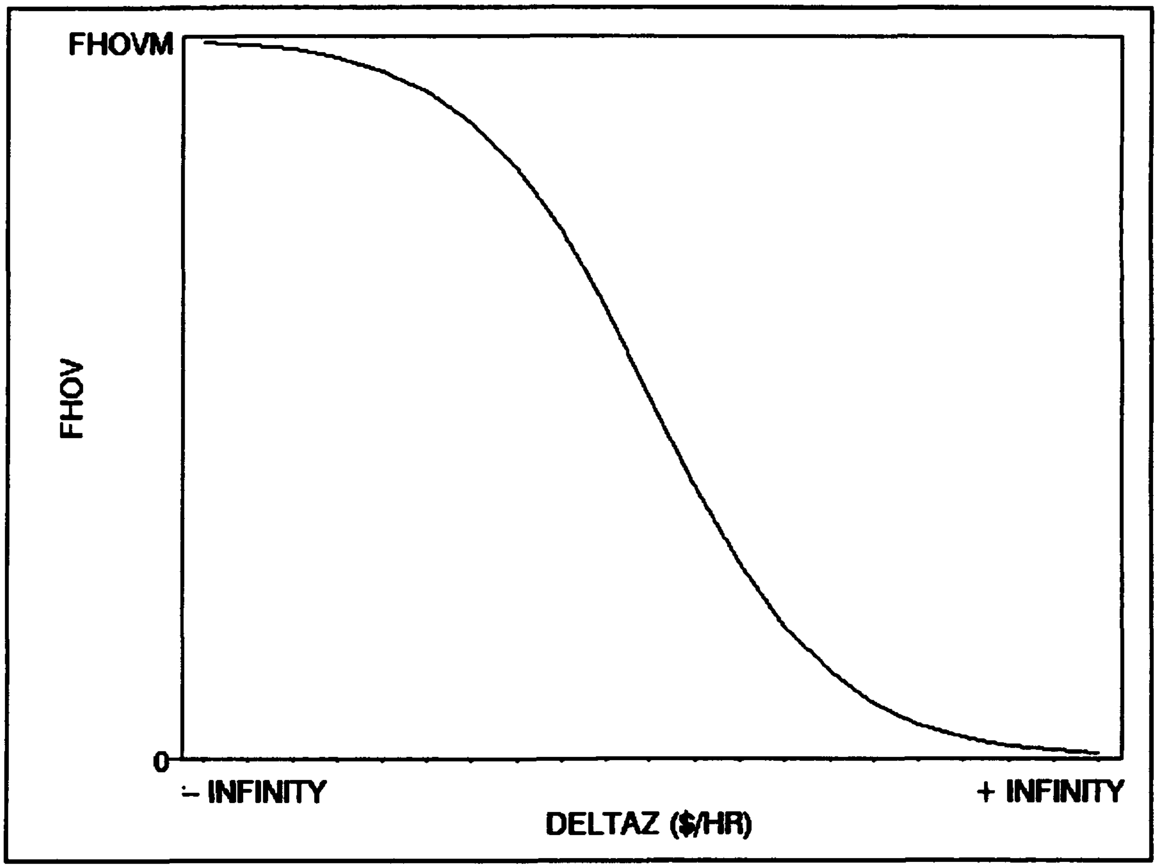

Figure 4 - Modal Split Model

A basic mathematical modal split model used in each approach of this project, adapted from the original problem. It is illustrated in Figure 4 and described by the following equation:

$$FHOV = \frac{FHOVM}{1 + e^{\frac{DELTAZ}{2}}}$$

where: FHOV = fraction of DEMAND that are HOV trips

FHOVM = maximum FHOV

DELTAZ = difference in disutility (\$/per-hr)

The difference in disutility (DELTAZ) is determined by subtracting the disutility experienced by LOVs from that experienced by HOVs (ZHOV - ZLOV). In this project, disutility is a function of the total time it takes to make a trip (wait time and travel time) and the cost associated with making the trip (cost of time and the cost of the toll). The difference in disutility is then used in the modal split model above to determine the fraction of total trip makers which are HOV trip makers (FHOV), which is in turn limited by FHOVM. The value for FHOVM used in this project was also taken from the original problem.

Now that the basic model has been described, the different approaches can be discussed. The following paragraphs cover each approach separately.

2.3.2 Approach 1

Wait time for HOVs and LOVs at the toll facility is not taken into consideration in Approach 1. As a result, HOV wait time (HWT) and LOV wait time (LWT) are set equal to zero. Travel time for HOVs and LOVs (HTT and LTT) was calculated by first calculating the travel speed using the speed-volume relationship. This relationship is derived from the basic speed-density-volume relationship.

The relationship between speed, density and volume is

defined in the following equation:

$$q=k\mu$$

where: q = volume (veh/hr)

k = density (veh/mi)

u = speed (mi/hr)

A linear relationship also exists between speed and density. This relationship can be expressed as

$$\mu=-\frac{k}{k_j}\mu_f+\mu_f$$

where: μ_f = free flow speed (mi/hr)

μ = speed (mi/hr)

k_j = jam density (veh/mi)

k = density. (veh/mi)

Solving the speed-density equation above for density and substituting into the speed-volume equation yields:

$$q=\mu k_j-\frac{\mu^2}{\mu_f}k_j$$

Solving this new speed-volume equation for speed gives us an equation in which speed can be determined from a given volume. The equation to determine speed in Approach 1 is as follows:

$$\mu=\frac{k_j\pm\sqrt{k_j^2-4\frac{k_j}{\mu_f}q}}{2\frac{k_j}{\mu_f}}$$

where μ = speed (mi/hr)

k_j = jam density (veh/mi)

μ_f = free flow speed (mi/hr)

q = volume (veh/hr)

In addition, this equation will also be used to determine the values for speed in Approaches 3 and 4, as mentioned in the discussions of these approaches. A graphical representation of the solution is shown in Figure 5. Once speed was calculated for HOVs and LOVs, travel time was then determined based on the length of the facility.

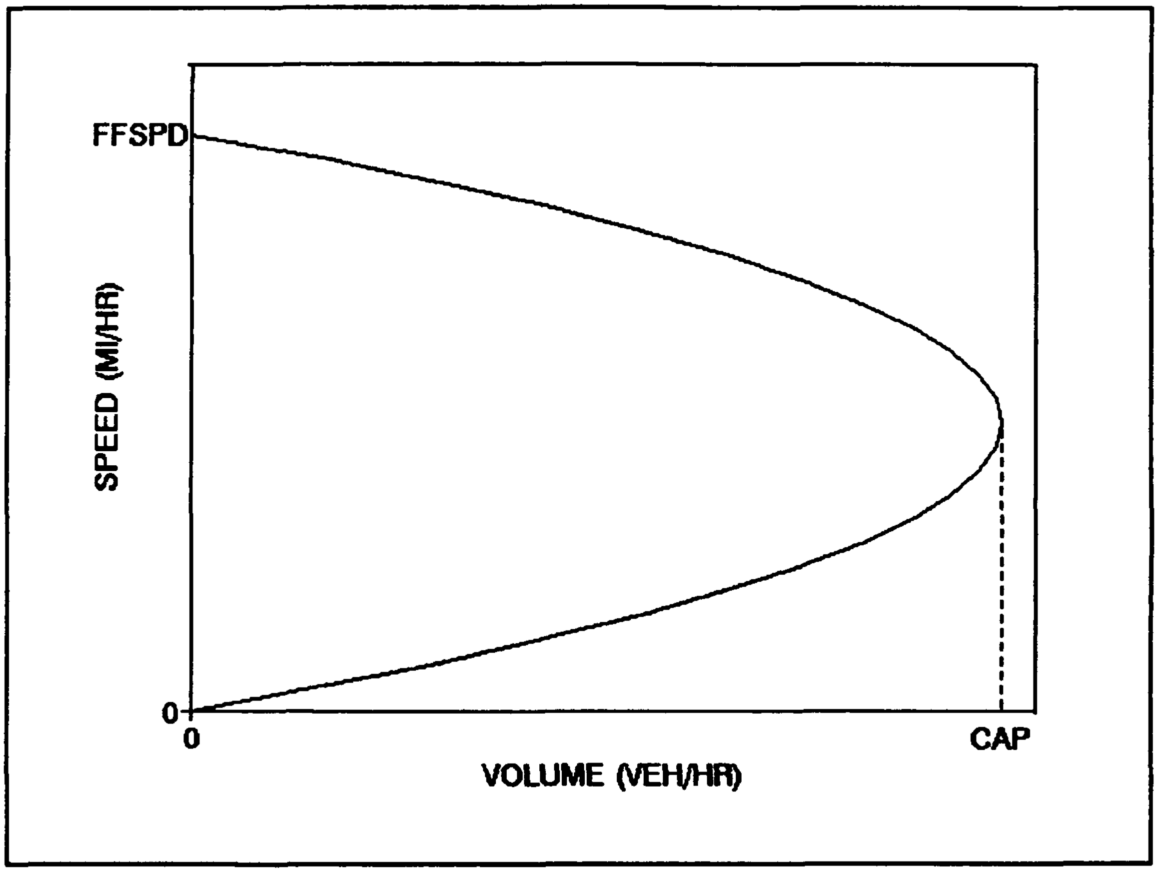

Figure 5 - Speed-Volume Relationship

The DYNAMO program implementing this equation to

determine travel time is included in Appendix B, Speed-Volume Model. Although wait time is neglected in this approach, it is assumed the toll facility is operational. As such, the downstream volume on the facility in this model is assumed to be limited by the toll gate service rates for HOVs and LOVs (HMU and LMU). The toll gate service rates are, in turn, limited to a value less than or equal to one half of the lane capacity. This assumption is made for two reasons. First, it prevents congestion downstream from the toll facility and second, it simplifies calculations since a volume greater than the lane capacity would not be consistent with the solution for speed and would result in the square root of a negative number. As a result of this assumption, the minimum speed attained will be equal to one half the downstream free speed, which in turn limits the maximum travel time.

2.3.3 Approach 2

As with Approach 1, the wait time at the toll facility is not taken into consideration for Approach 2. Wait time for HOVs and LOVs is again set equal to zero.

In this approach, travel time for HOVs and LOVs was calculated using a demand-capacity ratio model. This model was employed in determining the travel time in the original problem and is represented by the following equation:

$$\frac{TT}{FFTT} = e^{DCR}$$

where: TT = travel time (hr)

FFTT = free flow travel time (hr)

DCR = demand to capacity ratio

A graphical representation of the model is shown in Figure 6. Appendix C, Demand-Capacity Ratio Model, shows the DYNAMO program listing used to implement the model.

As with Approach 1, the toll facility is assumed to be operational even though wait time for HOVs and LOVs is assumed to be zero. In this approach, the need to limit the downstream volume by the lane capacity is not necessary since the demand-capacity ratio model can accommodate volumes greater than lane capacity. The downstream volume would in fact be limited by the maximum toll gate service rate, which in actuality could be a value much greater than one half of the lane capacity. However, in order to provide consistency between the approaches and allow for comparisons, the toll gate service rate will be limited to one half of the lane capacity.

2.3.4 Approach 3

In Approach 3, travel time is determined as discussed for Approach 1, using the speed-volume relationship to calculate travel speed which is then used to calculate travel time. Reference section 2.3.2 for the development and discussion of this relationship. Wait time for HOVs and LOVs is not assumed to be zero but rather is determined using a deterministic queuing model.

A plot of the cumulative demand and cumulative capacity

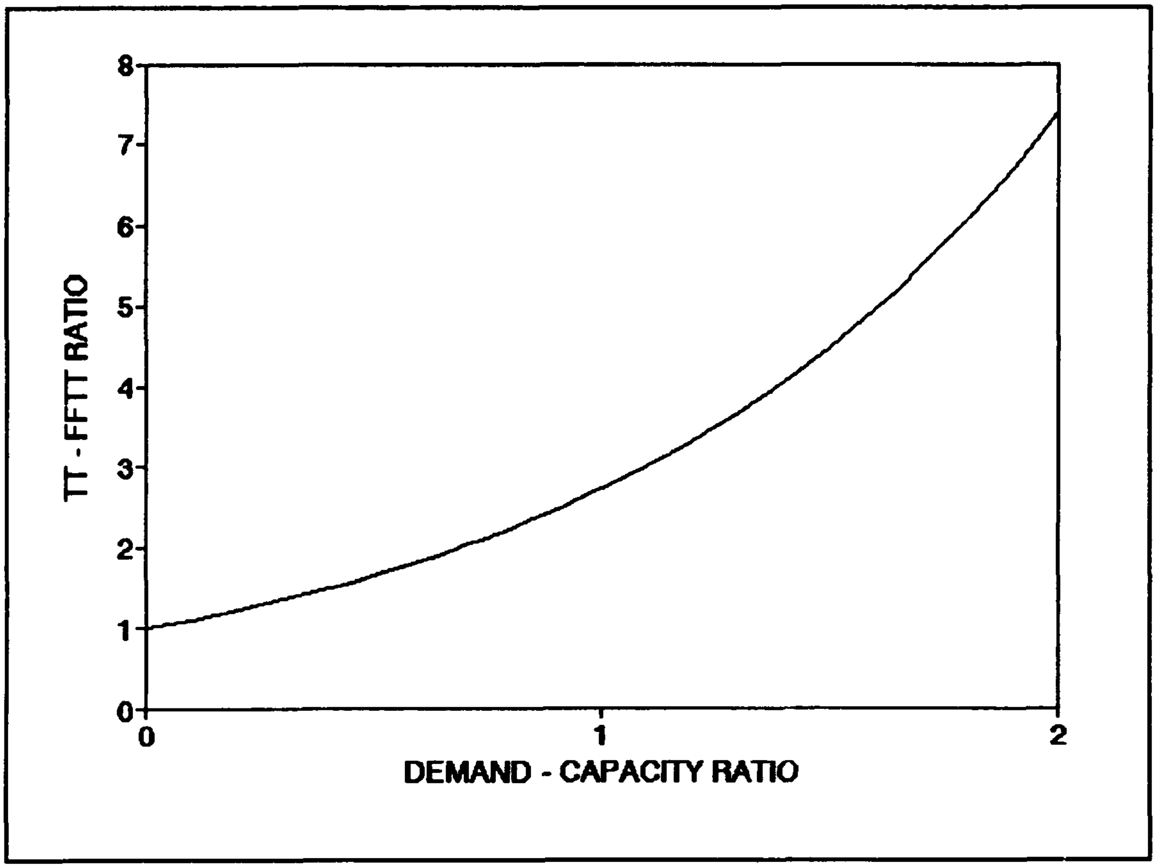

Figure 6 - Demand to Capacity Ratio Model

over time for a highway facility is one way to estimate the impact of highway congestion. Figure 8 is an example of this type of plot. From a plot of cumulative demand and capacity, operational characteristics of the facility can be derived. For example, the number of vehicles affected, the maximum number of vehicles in the queue as well as the maximum queue length can be estimated. Given the duration of excess demand, the delay experienced by an individual vehicle as well as the total vehicle-hours of delay can also be estimated. Finally, a cumulative demand and capacity plot over time can be used to

estimate the average delay experienced per vehicle (4). The average delay per vehicle is determined by calculating the total delay experienced by all vehicles and dividing by the total number of affected vehicles. In Approach 3, the average delay experienced by HOVs and LOVs at the toll facility is calculated using this approach and illustrated in the following discussion.

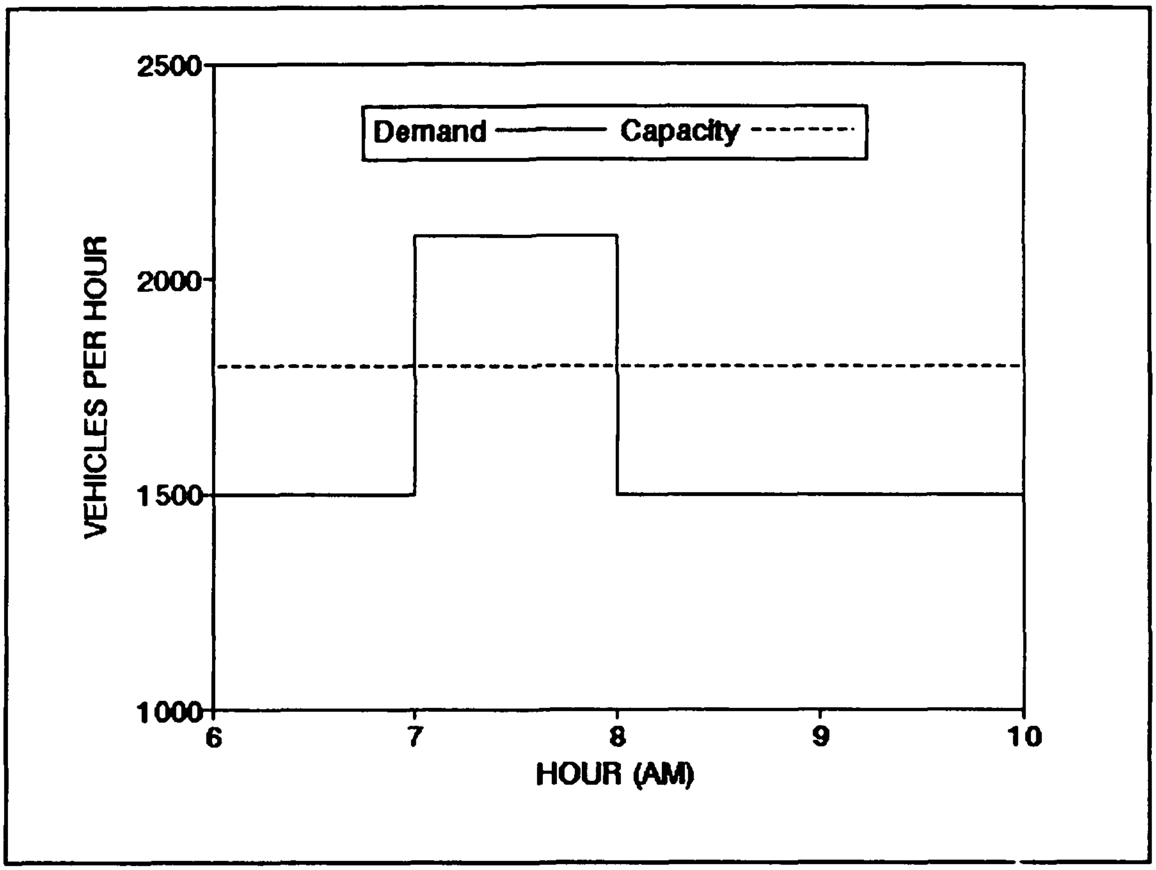

Figure 7 - Demand verses Capacity Plot

In order to use the cumulative demand and capacity plot to estimate average delay per vehicle, a plot of demand verses capacity over time must be made. As an example, assume a

single lane facility has a constant capacity of 1800 vehicles per hour. Initially, demand is 1500 vehicles per hour and then increases to 2100 vehicles per hour for a one hour period and then returns to the initial demand. Figure 7 shows the demand verses capacity plot for these conditions.

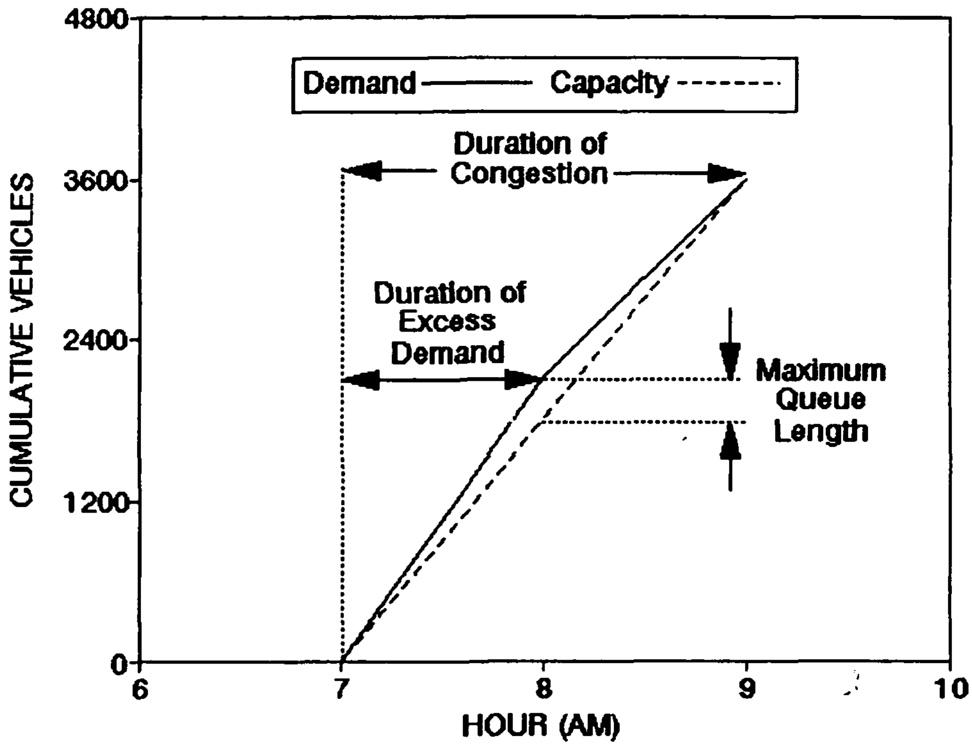

Figure 8 - Cumulative Demand verses Capacity Plot

At the point in time which demand exceeds capacity, a plot for cumulative demand verses cumulative capacity begins. The plot ends at the point in time when cumulative demand becomes less than cumulative capacity. The plot of cumulative demand verses cumulative capacity for this example is shown in

Figure 8.

The total delay experienced by all vehicles is the area between the cumulative demand and cumulative capacity curves shown in Figure 8 and is expressed in vehicle-hours. Total delay is equal to one half of the product of the duration of congestion and the maximum queue length. The maximum queue length can, in turn, be expressed as the product of the duration of excess demand and the difference between excess demand and capacity. Therefore, the total delay experienced by all vehicles can be expressed in equation form as

$$TOTAL\ DELAY=\frac{1}{2}*DUR_c*DUR_{ed}*(EXCESS\ DEMAND-CAPACITY)$$

where: DUR_c = duration of congestion (hr)

DUR_{ed} = duration of excess demand (hr)

The total number of vehicles affected is the product of the duration of congestion and the lane capacity or

$$TOTAL\ VEHICLES\ AFFECTED=DUR_c*CAPACITY$$

Since the average delay per vehicle is the total delay experienced by all vehicles divided by the total number of vehicles affected, the two equations can be combined and simplified to yield

$$\frac{AVERAGEDELAY}{VEHICLE}=\frac{DUR_{ed}*(EXESS\ DEMAND-CAPACITY)}{2*CAPACITY}$$

Continuing with our example from above, the average delay per vehicle can be shown to be 5 minutes.

$$\frac{AVERAGE\ DELAY}{VEHICLE}=\frac{1HR*(2100\frac{VEH}{HR}-1800\frac{VEH}{HR})}{2*1800\frac{VEH}{HR}}=5\ MINS$$

As implemented in the DYNAMO program, the average delay per vehicle is expressed as HOV wait time or LOV wait time (HWT or LWT) as required. The variables HDEL and LDEL represent the numerator in the equation for average delay per vehicle while HVEH and LVEH represent the denominator. In order to study the effects of different service rates at the toll facility, the variables HMU and LMU are introduced and used to specify toll gate service rate (HTGSR and LTGSR) for each lane. The HOV and LOV toll gate service rate values were the values used for the capacity in the equation for average delay per vehicle. The duration of excess demand (DUR_{ed}) is represented by the variable DUR. The complete DYNAMO program listing for Approach 3 is found in Appendix D, Cumulative Demand/Capacity Model.

2.3.5 Approach 4

Approach 4 utilizes the speed-volume relationship to determine travel time as in Approaches 1 and 3. The speed-volume relationship is developed and discussed in section 2.3.2. The average wait time for HOVs and LOVs is not assumed to be zero in this approach and is determined by using an enhanced cumulative demand and cumulative capacity deterministic queuing model to calculate total delay. Total delay is then used to calculate average delay per vehicle as

in Approach 3. The enhance approach accounts for the additional vehicles caught up in the area encompassed by the growing queue.

As in Approach 3, total delay experienced by all vehicles is equal to one half of the product of the duration of congestion and the maximum queue length. The maximum queue length, however, is expressed as the product of the duration of excess demand, the density of vehicles in the queue, and the queue growth rate. Total delay is therefore expressed as

$$TOTAL\ DELAY = \frac{1}{2} * DUC_c * DUR_{ed} * k_4 * S$$

where: DUR_c = duration of congestion (hr)

DUR_{ed} = duration of excess demand (hr)

k_4 = queue density (veh/mi)

S = queue growth rate (mi/hr).

The total number of vehicles affected is the product of the duration of congestion and lane capacity as before. Combining the new equation for total delay and the equation for the total number of vehicles affected, the average delay per vehicle becomes

$$\frac{AVERAGE\ DELAY}{VEHICLE} = \frac{DUR_{ed} * k_4 * S}{2 * CAPACITY}$$

The queue growth rate (S) represents the speed in which the queue of vehicles either grows or collapses from behind a bottleneck. A discussion the queue growth rate, adapted from McShane (4), follows.

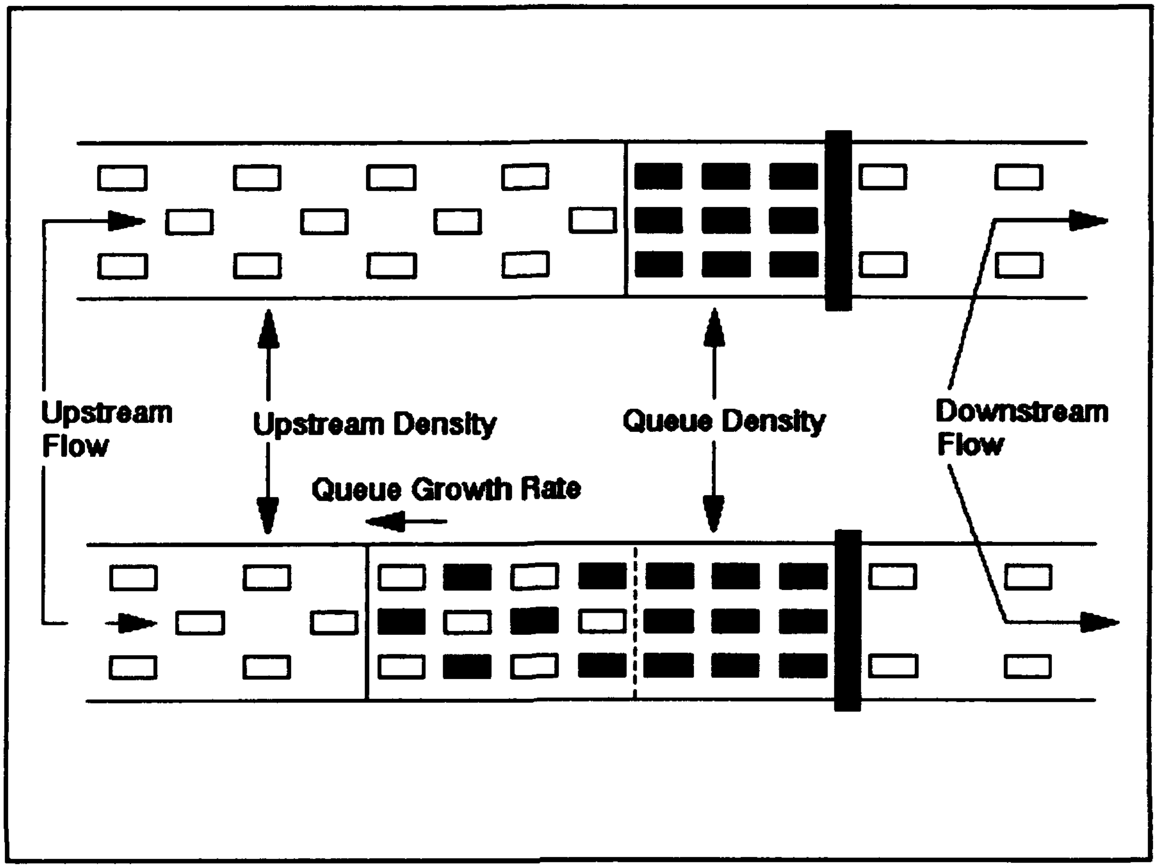

Figure 9 - Queue Rate of Growth

Consider Figure 9, which illustrates a queuing situation at an arbitrary point in time and one hour later. There are two elements which comprise the expanded queue. First, there is the hour's accumulation of vehicles, represented by the upstream flow rate less the downstream flow rate. Second, the expanded queue includes the area in which there were already vehicles at the upstream density. The growth of the queue during the hour can then defined as

$$[(q_1-q_2)+S*k_1] \textit{ vehicles}$$

where: q_1 = upstream volume (veh/lane)

q_2 = downstream volume (veh/lane)

k_1 = upstream density (veh/mi)

S = queue rate of growth (mi/hr)

and where the queue rate of growth is unknown. From Figure 9, one can see the growth during the hour is also be defined by the queue density and the queue rate of growth. Queue growth can also be defined as

$$S*k_4 \text{ vehicles}$$

where: k_4 = queue density. (veh/mi)

S = queue rate of growth (mi/hr)

Both equations define the number of vehicles accumulated in the queue during the elapsed hour. Setting the equations equal to each other and solving for the queue rate of growth yields

$$S=\frac{q_1-q_2}{k_4-k_1}$$

A positive value for the queue growth rate indicates the queue is increasing in length at the rate calculated while a negative value indicates the queue is collapsing or decreasing.

In order to illustrate the enhanced cumulative demand and capacity method, an example is presented, extending the example discussed in Approach 3. The facility illustrated has a capacity of 1800 vehicles per hour with an initial demand of

1500 vehicles per hour, increasing to 2100 vehicles per hour for one hour and then returning to the previous level of demand. In order to implement the enhanced cumulative demand and capacity method, additional information is required. Assume the upstream capacity of the facility is 2400 vehicles per hour with a jam density of 120 vehicles per mile throughout the entire facility. This would allow an upstream free speed of 80 miles per hour and a free speed for the portion of the facility experiencing excess demand of 60 miles per hour. From the density-volume relationship, which is discussed later, the queue density is 90 vehicles per mile and the upstream density is approximately 39 vehicles per mile.

Using the values from above, the queue rate of growth becomes

$$S=\frac{2100\frac{VEH}{HR}-1800\frac{VEH}{HR}}{90\frac{VEH}{MI}-39\frac{VEH}{MI}}=5.88\frac{MI}{HR}$$

Under these conditions, this value for the queue rate of growth indicates the queue is growing at a rate of 5.88 miles per hour. Substituting the queue growth rate into the equation for the average delay per vehicle indicates an average delay of almost 9 minutes.

$$\frac{AVERAGE\ DELAY}{VEHICLE}=\frac{1\ HR*90\frac{VEH}{MI}*5.88\frac{MI}{HR}}{2*1800\frac{VEH}{HR}}=8.82\ MINS$$

The additional delay of almost 4 minutes over Approach 3 is

the result of taking into consideration the vehicles caught up in the growing queue. This example points out that these extra vehicles actually have a significant effect on the average delay experienced by each vehicle.

In order to implement the equation for average delay per vehicle in the DYNAMO program, values for upstream density, queue density, upstream volume, and downstream volume are required for both HOVs and LOVs. These values can then be used to find the HOV and LOV queue growth rate. For this analysis, additional assumptions needed to be made as in the example.

The upstream capacity was assumed to be 2800 vehicles per lane-hour with a jam density assumed to be 120 vehicles per lane-mile. Given these assumptions, the upstream free speed (UFSPD) can be determined to be approximately 93.33 miles per hour. Upstream volume for HOVs (HQ1) is assumed to be equal to the number of HOVs divided by the number of HOV lanes (HLANES). The value of LOV upstream volume (LQ1) is calculated in a similar manner, dividing the number of LOVs by the number of LOV lanes (LLANES).

Given the values for HOV and LOV upstream volumes, the HOV and LOV upstream densities (HK1 and LK1) are determined using the volume-density relationship. This relationship is derived from the basic speed-density-volume relationship.

From the speed-density-volume relationship discussed in Approach 1, density can be expressed as

$$k=\frac{q}{\mu}$$

where: k = density (veh/mi)

q = volume (veh/hr)

u = speed (mi/hr).

Substituting the speed-density equation discussed in section 2.3.2 into the above equation for speed and solving for density yields:

$$k=\frac{\mu_f \pm \sqrt{\mu_f^2-4\frac{\mu_f}{k_j}q}}{2\frac{\mu_f}{k_j}}$$

where: k = density (veh/mi)

μ_f = free flow speed (mi/hr)

k_j = jam density (veh/mi)

q = volume (veh/hr).

A graphic of the volume-density relationship is shown in Figure 10.

Downstream volumes for HOVs and LOVs (HQ2 and LQ2) were assumed to be the lessor of the respective toll gate service rate or the upstream volume. If upstream volume is less than the service rate, vehicles pass through the toll facility with no waiting. On the other hand, if upstream volume is greater than the toll gate service rate, the toll gate service rate limits the downstream volume and a queue forms.

The values for HOV and LOV queue densities (HQ4 and LQ4)

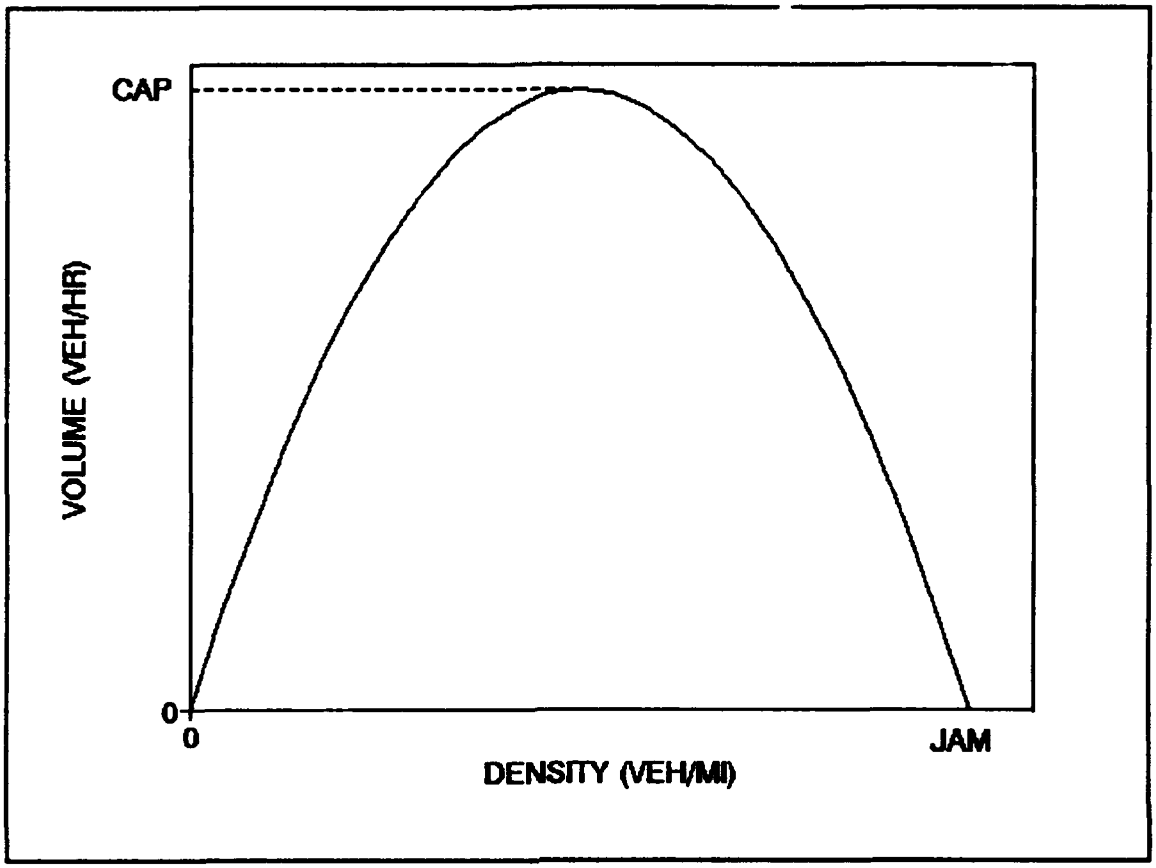

Figure 10 - Volume-Density Relationship

were calculated using the values for the HOV and LOV toll gate service rate as the volume in the density-volume equations for the upstream conditions. Finally, the HOV and LOV queue growth rate (HS and LS) was calculated. Queue growth rate was set to zero if the calculated value was negative.

The average delay per vehicle is expressed as HWT or LWT as required. As in Approach 3, the variables HDEL and LDEL, represent the numerator in the equation for average delay per vehicle, and HVEH and LVEH represent the denominator. The variables HMU and LMU are again used in order to study the

effects of different service rates at the toll facility. The duration of excess demand (DUR_{ed}) is represented by the variable DUR. The DYNAMO program listing implementing this approach is included in Appendix E, Enhanced Cumulative Demand/Capacity Model.

This concludes the discussion on the development of the four approaches. Once the models were developed, each approach model was verified to ensure the results were as expected.

2.4 Model Verification

Verification of a computer model is the process of determining if the model performs as intended. For this project, each approach model was verified by comparing the model results with results that were calculated manually. A detailed discussion of the model results are presented in the next chapter.

CHAPTER 3 SENSITIVITY ANALYSIS

Sensitivity analysis explores model behavior in light of reasonable changes to model structure or parameter values. The second step in this project will examine the sensitivity of the model to the structure changes represented by the various approaches as well as the sensitivity of the approaches to changes in parameter values. Before proceeding with the analysis, a brief description of three types of model sensitivity is presented.

The sensitivity of a model can be examined from three perspectives (5). First, numerical sensitivity can be described as the change in the numerical output of a model due to changes in structure or parameter values. All models exhibit numerical sensitivity to some extent. Behavioral sensitivity describes the change in the behavior of the model due to changes in structure or parameter values. This type of sensitivity focuses on the general trend of the model output. In the case of a DYNAMO model, behavioral sensitivity is concerned with the pattern of the output graph over time. Finally, there is policy sensitivity, which examines the results of policy implementation over reasonable model structure changes or ranges of parameter values.

For this project, all three types of sensitivity are discussed, focusing on numerical sensitivity. Each approach is examined as to it's numerical sensitivity to changes in

parameter values. Afterwards, a brief discussion on behavioral and policy sensitivity is presented based on the results of the numerical sensitivity analyses.

3.1 Numerical Sensitivity

Numerical sensitivity analysis examines the impact of changes to parameter values on model output. The fraction of total demand that utilize HOVs (FHOV) will be the variable of interest in this analysis. The parameters examined included the decision variables for the HOV and LOV cost of the toll (HTOLL and LTOLL) and the toll gate service rate for and LOVs (LMU). Model sensitivity to the parameters for the cost of time (CTIME) and average vehicle occupancy for HOVs and LOVs (HAVO and LAVO) was also explored. The relative impact of changes to these last parameters gives an indication of the degree of accuracy to which values for these parameters would need to be estimated for use in the model.

Numerical sensitivity of the fraction of total trip makers that are HOV (FHOV) in each modeling approach will be examined as the values for HOV and LOV toll cost (HTOLL and LTOLL) are changed between $0 and $3 per vehicle and the LOV toll gate service rate (LMU) is changed between 787.5 and 1050 vehicles per gate-hour. These parameters are changed in order to examine various road pricing, metering and HOV handling strategies within each model. Seven different strategies are employed and the results compared to the base run or base strategy. The base strategy assumes there are no tolls

assessed on either types of vehicles and the toll gate service rates are such that they will equal the downstream capacity for each lane. Table B identifies the decision variable values for the base strategy as well as the decision variable values for each of the seven other strategies examined.

Table B - Strategy Summary

Strategy	HOV Cost of Toll (HTOLL)	LOV Cost of Toll (LTOLL)	Toll Gate Service Rate (LMU)
Base	$0/veh	$0/veh	1050 veh/hr
1	$0/veh	$3/veh	1050 veh/hr
2	$3/veh	$0/veh	1050 veh/hr
3	$3/veh	$3/veh	1050 veh/hr
4	$0/veh	$0/veh	787.5 veh/hr
5	$0/veh	$3/veh	787.5 veh/hr
6	$3/veh	$0/veh	787.5 veh/hr
7	$3/veh	$3/veh	787.5 veh/hr

In the base strategy, the HOV and LOV cost of toll (HTOLL and LTOLL) will be $0 per vehicle and the LOV toll gate service rate will be set at 1050 vehicles per gate-hour. Strategy 1 will examine the effects of increasing the LOV toll cost (LTOLL) from $0 to $3 per vehicle while the LOV toll gate service rate remains unchanged. The effects of increasing the cost of the tolls for HOVs (HTOLL) from $0 to $3 per vehicle while the LOV toll gate service rate remains at 1050 vehicles per hour will be examined in Strategy 2. Strategy 3

increases the toll cost for both HOVs and LOVs from $0 to $3 per vehicle. Strategies 4 through 7 are basically extensions of the base strategy and Strategies 1 through 3 respectively, decreasing the LOV toll gate service rate to 787.5 vehicles per hour.

Sensitivity of the fraction of total trip makers that use HOVs (FHOV) to changes in the cost of time (CTIME), the average vehicle occupancy for HOVs (HAVO) and LOVs (LAVO) is also examined. Although these parameters are not decision variables, this analysis provides some indication as to the relative impact changes to these parameters have on the fraction of demand that utilize HOVs (FHOV). If changes to these values have a significant impact, it would indicate these values will need to be carefully estimated. On the other hand, little or no impact would indicate less attention might be needed in estimating these values. The sensitivity of FHOV to the cost of time (CTIME) will be examined through a range of values between $8 per hour to $10 per hour. Sensitivity to average vehicle occupancy (HAVO and LAVO) will be examined using a range of values between 3 and 4 for HOV average vehicle occupancy and a range of values between 1 and 2 for LOV average vehicle occupancy.

3.1.1 Approach 1 Numerical Sensitivity

Table C shows the sensitivity of the fraction of total trip makers that are HOV trip makers (FHOV) to the seven strategies. From these results it appears FHOV is most

Table C - FHOV Sensitivity (Approach 1)

Strategy	FHOV	% Change
Base	.2698	-
1	.3588	33.0
2	.2258	- 16.3
3	.3372	25.0
4	.2188	- 18.9
5	.3336	23.6
6	.1716	- 36.4
7	.3028	12.2

sensitive to Strategies 1 and 6. Increasing the LOV cost of the toll (LTOLL) increases FHOV by 33 percent over the base strategy. Given an HTOLL value of $3 per vehicle and an LTOLL value of $0 per vehicle and decreasing the service rate from 1050 to 787.5 vehicles per gate hour decreases the FHOV by more than 36 percent as compared to the base strategy.

3.1.3 Approach 2 Numerical Sensitivity

Table D shows the sensitivity of the value for FHOV in Approach 2 to the implementation of the different strategies. Strategies 1 and 6 again have the largest impact on FHOV, as in Approach 1. Although the magnitude of the changes are slightly less, the direction of the change in FHOV remains the same across both approaches.

3.1.4 Approach 3 Numerical Sensitivity

The sensitivity of the value for FHOV to the strategies

Table D - FHOV Sensitivity (Approach 2)

Strategy	FHOV	% Change
Base	.2880	-
1	.3623	25.8
2	.2515	- 12.7
3	.3437	19.3
4	.2503	- 13.1
5	.3431	19.1
6	.2098	- 27.2
7	.3182	10.5

implemented in Approach 3 is shown in Table E. Strategy 1 again has a great impact on the value for the fraction of total trip makers that utilize HOVs (FHOV). In addition, Strategy 5, decreasing the LOV toll gate service rate with HTOLL and LTOLL at $0 and $3 per vehicle, also has a significant impact on FHOV, increasing over 23 percent as compared to the base strategy.

3.1.5 Approach 4 Numerical Sensitivity

Finally, the value of FHOV in Approach 4 demonstrates a similar sensitivity when compared to Approach 3. Strategies 1 and 5 again have the greatest impact on the fraction of total trip makers that utilize HOVs (FHOV) as compared to the base strategy. The sensitivity results for Approach 4 are shown in Table F.

It can be seen that the value for the fraction of total

Table E - FHOV Sensitivity (Approach 3)

Strategy	FHOV	% Change
Base	.2967	-
1	.3630	22.3
2	.2655	- 10.5
3	.3459	16.6
4	.3080	3.8
5	.3668	23.6
6	.2803	- 5.5
7	.3515	18.5

trip makers that utilize HOVs (FHOV) is sensitive to changes in the values for all parameters in each approach. This result is as expected based on the earlier comments regarding numerical sensitivity. Although FHOV is sensitive to changes in parameter values in each approach, the magnitude and direction of the changes were not always consistent with the same changes in parameters between approaches. For example, in Approaches 1 and 2, the change in FHOV due to a 25 percent decrease in LOV toll gate service rate (LMU) from 1050 to 787.5 vehicles per hour is -18.9 and -13.1 percent respectively. However, in Approaches 3 and 4, this same change in toll gate service rate produced a change in FHOV of 3.8 and 7.8 percent respectively. Possible explanations for the variations in changes to FHOV will be examined in Chapter 4, Discussions and Conclusion.

Table F - FHOV Sensitivity (Approach 4)

Strategy	FHOV	% Change
Base	.3092	-
1	.3649	18.0
2	.2854	- 7.7
3	.3498	13.1
4	.3334	7.8
5	.3753	21.4
6	.3144	1.7
7	.3642	17.8

Before concluding this section on numerical sensitivity and moving on to the discussions of behavioral and policy sensitivities, the sensitivity of each approach to the cost of time (CTIME) and the average vehicle occupancy for HOVs and LOVs (HAVO and LAVO) was examined. Reference Figures 11 through 13 for the following discussion.

From the graphs in Figures 11, 12 and 13, each approach appears to be fairly insensitive to changes in the cost of time (CTIME) and the average vehicle occupancy for HOVs (HAOV), particularly Approach 4. However, each approach demonstrates a significant sensitivity to changes in value for LOV average vehicle occupancy (LAVO). It is interesting to note Approach 4 demonstrates the greatest sensitivity to changes in LAVO. This indicates there is a much greater need to be more accurate in the estimate for LOV average vehicle

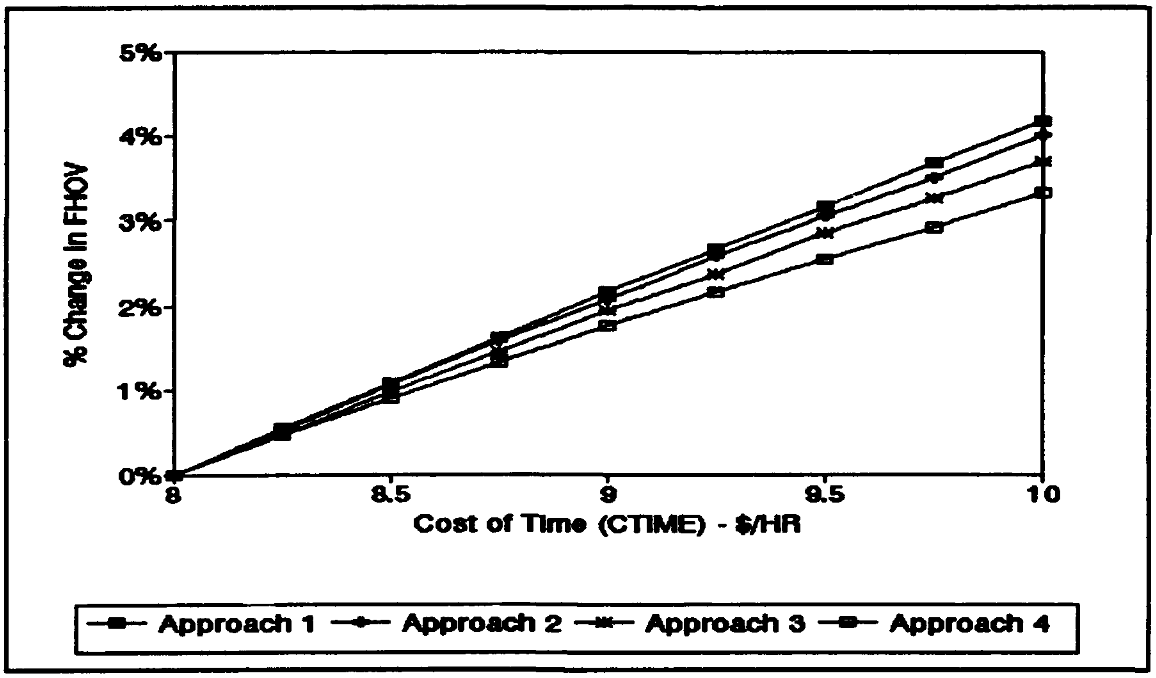

Figure 11 - Sensitivity to CTIME

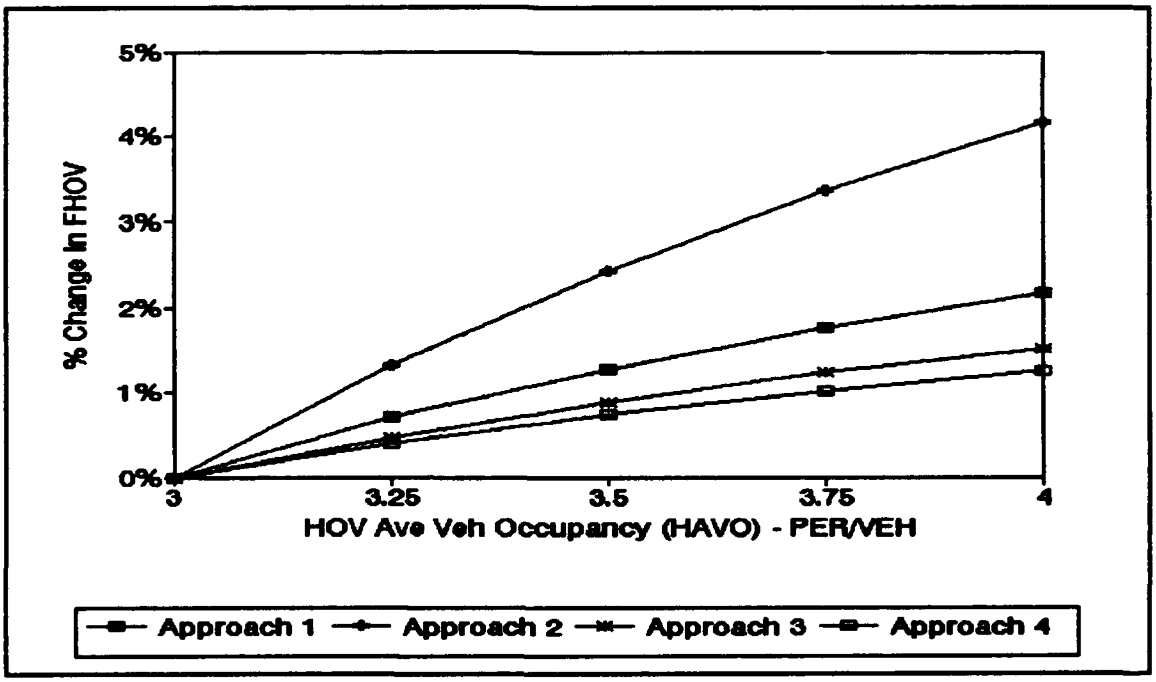

Figure 12 - Sensitivity to HAVO

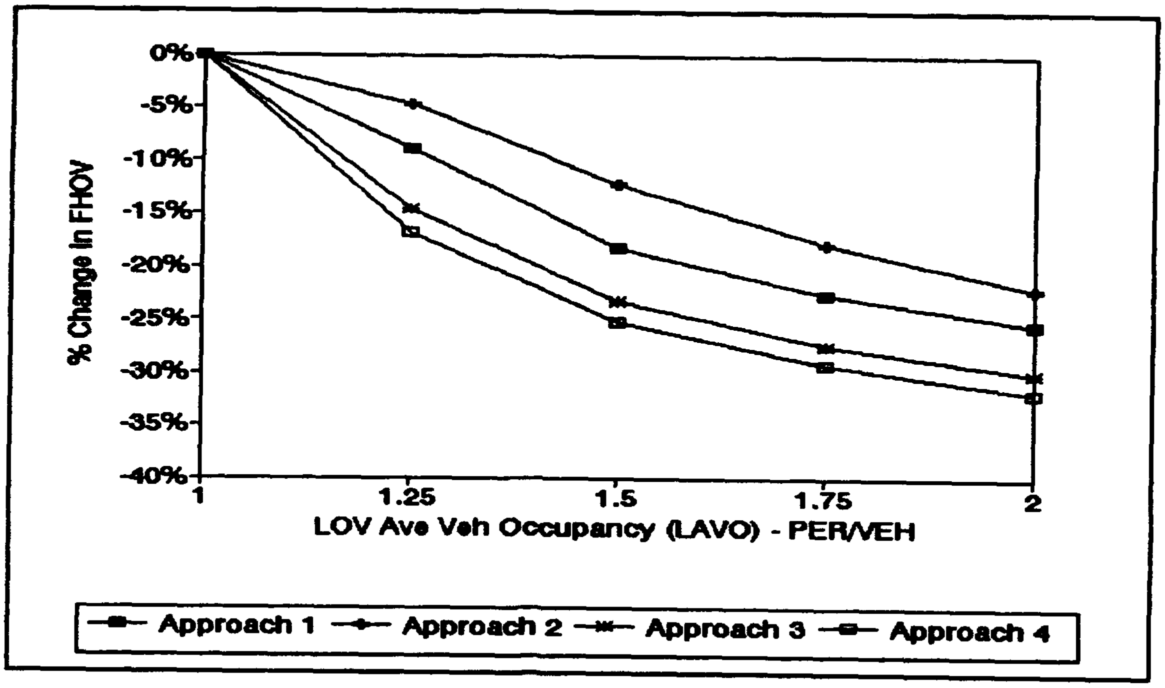

Figure 13 - Sensitivity to LAVO

occupancy than for the HOV average vehicle occupancy and cost of time.

3.2 Behavioral Sensitivity

Within each approach, the general behavior of the fraction of total trip makers that utilize HOVs (FHOV) remained consistent as different strategies were implemented. In this case, consistent behavior means the value for FHOV attained a constant value with respect to time for each strategy. Granted, the values for FHOV changed from strategy to strategy within each approach, but the general behavior remained the same. Indeed, setting the initial value for FHOV (FHOVN) to a value of 0 or to the equilibrium value attained in the base strategy or to a value of 1, the behavior of the

value for FHOV in each case remained the same: a constant value was attained over time. It appears the behavior of the model for each approach is insensitive to the implementation of the various strategies.

Comparing the results of the different approaches, the general model appears to exhibit behavior insensitivity to minor structural changes as well. In this case, minor changes to the model formulation does not change the basic model behavior, that of attaining a constant value for the fraction of total trip makers that utilize HOVs (FHOV) over time. Although the behavior of the model is not sensitive to changes in parameter values or to various formulations in structure, this does not mean the approach is an accurate reflection of the real system.

3.3 Policy Sensitivity

Systems dynamics models are generally formulated for the purpose of exploring the general effects of different strategies on variables of interest rather than quantitative results. As such, it would be imperative to know if a policy is sensitive to reasonable changes to model structure or to reasonable ranges for the parameters. In other words, policy sensitivity seeks to discover if model based policy conclusions change with reasonable changes to the model. Examining the results produced in the discussion of numerical sensitivity reveals the general model exhibits policy sensitivity across the approaches.

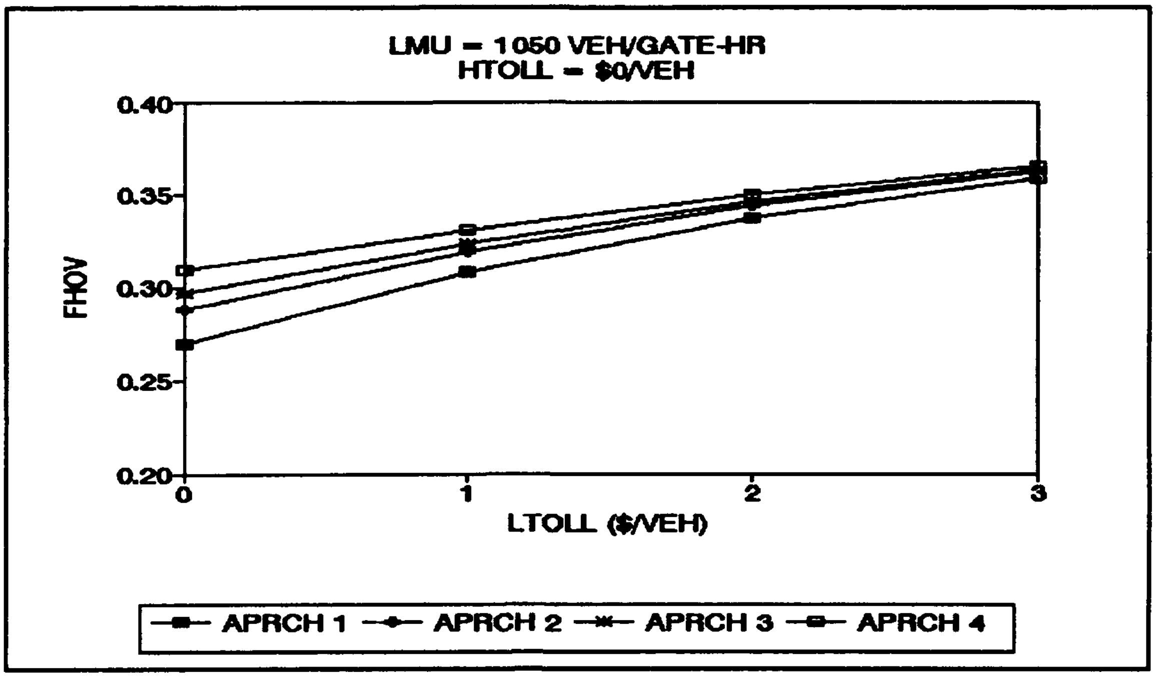

Figure 14 - Strategy 1

In order to illustrate policy sensitivity, consider Figure 14. This graph illustrates the effect of implementing Strategy 1, increasing the LOV toll cost (LTOLL) from $0 to $3 per vehicle, on the fraction of total trip makers that utilize HOVs (FHOV). Upon examination of Figure 14, it can be seen that each of the four approaches predicts the same end result: an increase in the cost of the toll for LOVs (LTOLL) increases the number of trip makers using HOVs (FHOV). Figures 15 and 16 illustrate the effects of implementing Strategies 2 and 3 respectively. In each of these figures, is can be seen that each of the approaches would predict the same end result.

Now consider the graphs of Strategies 4 through 7, shown in Figures 17 through 20. It is obvious that conclusions made

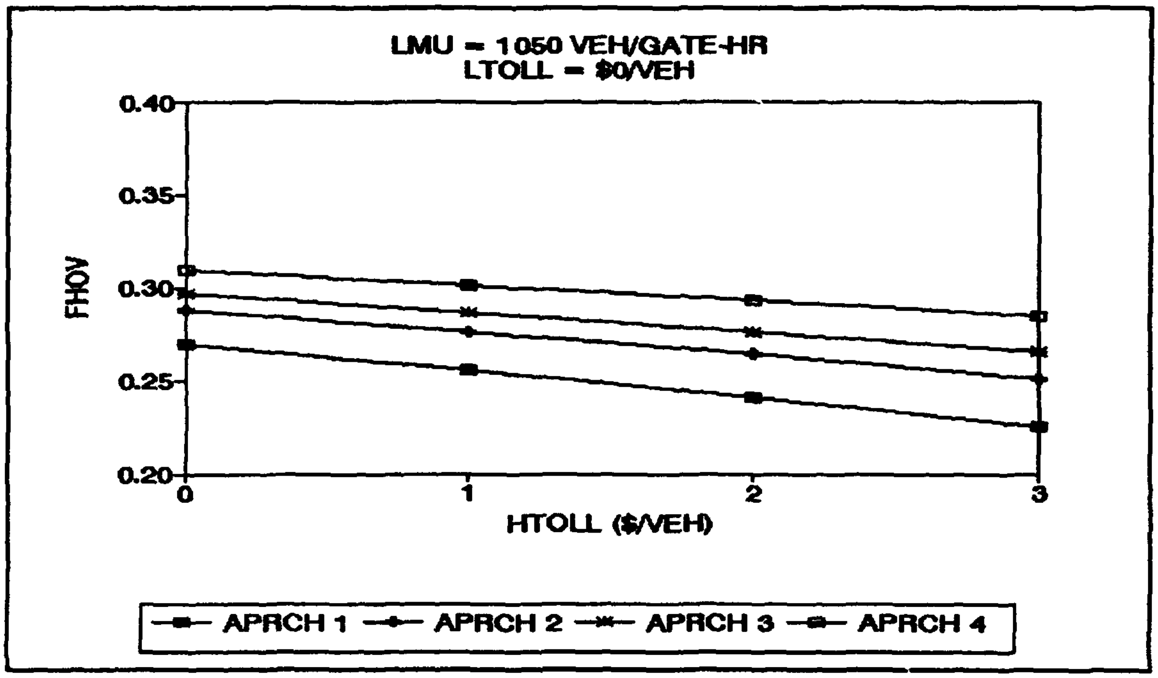

Figure 15 - Strategy 2

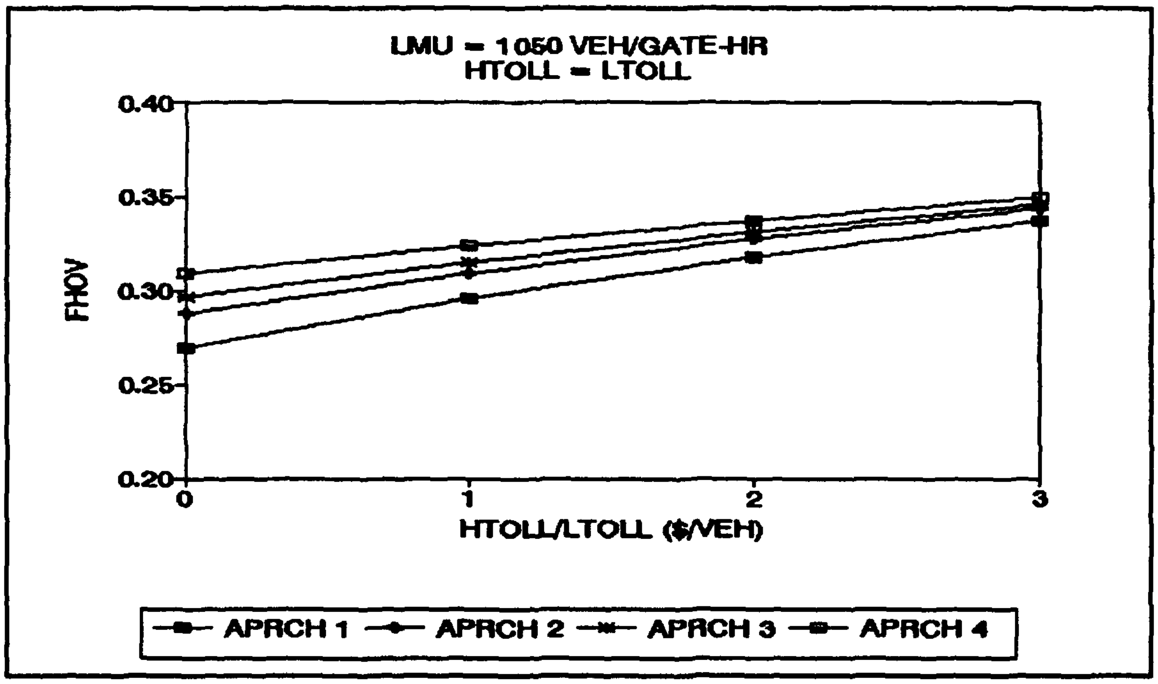

Figure 16 - Strategy 3

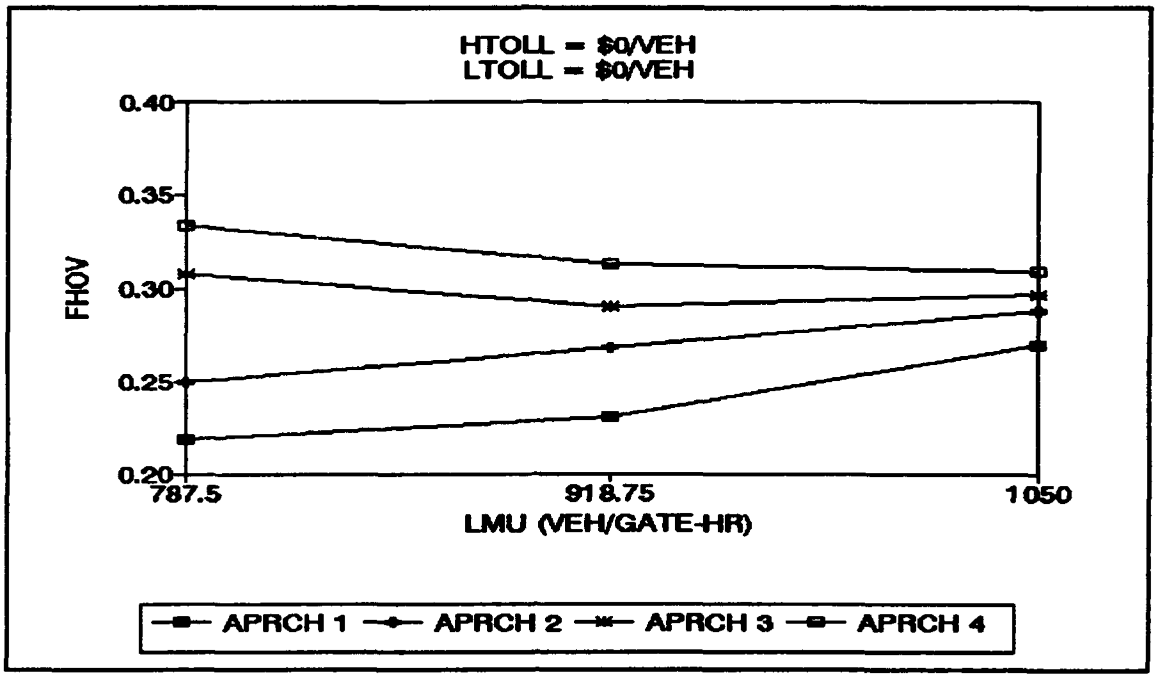

Figure 17 - Strategy 4

based on Approaches 1 and 2 would be the opposite of those made based on Approaches 3 and 4. Using the results of Approaches 1 and 2, the conclusion could be made that increasing the LOV toll gate service rate (LMU) would increase the fraction of total trip makers that use HOVs (FHOV) while the results from Approaches 3 and 4 would indicate an increase in LMU would lead to a decrease in FHOV. If the goal was to increase FHOV, the results of Approaches 3 and 4 would effectively reverse the policy made based on the results of Approaches 1 and 2, hence a complete policy reversal.

The general model does indeed exhibit policy sensitivity as a result of changes in model structure. A determination must now be made as to which of the approach approaches will

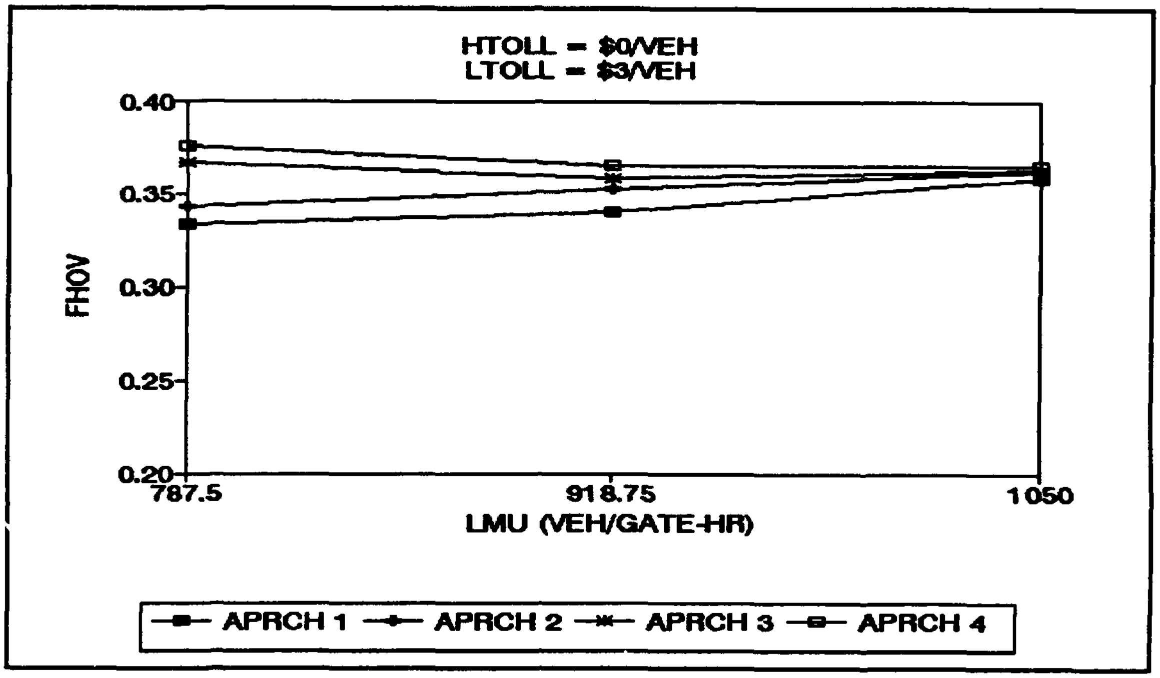

Figure 18 - Strategy 5

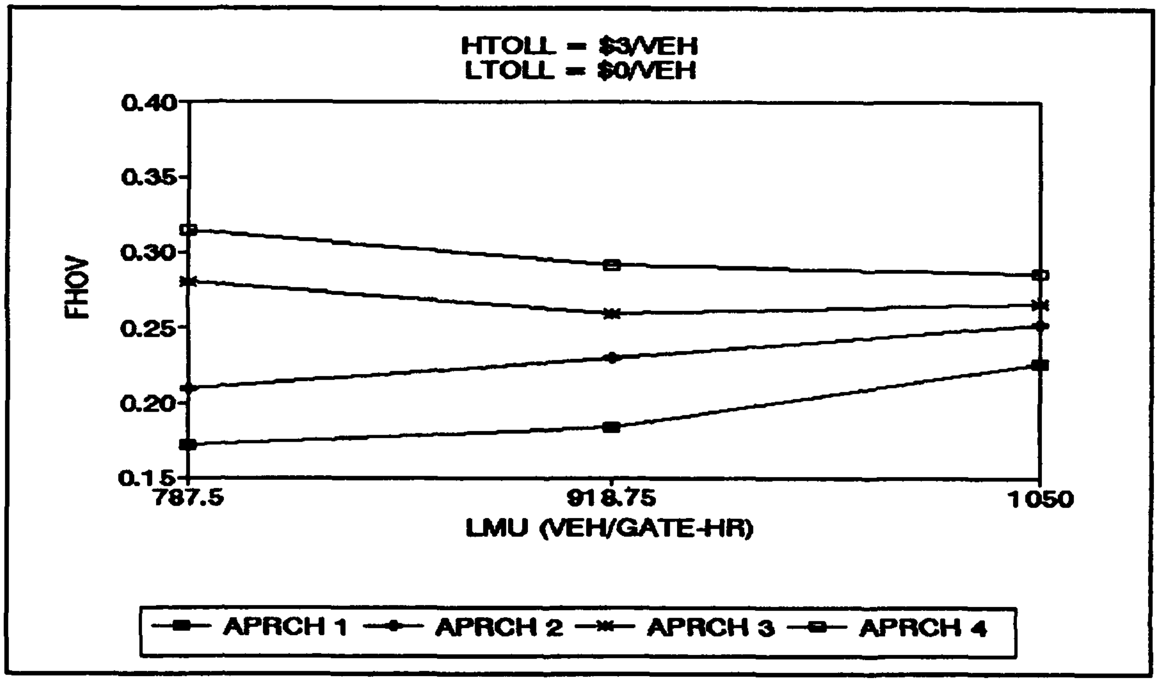

Figure 19 - Strategy 6

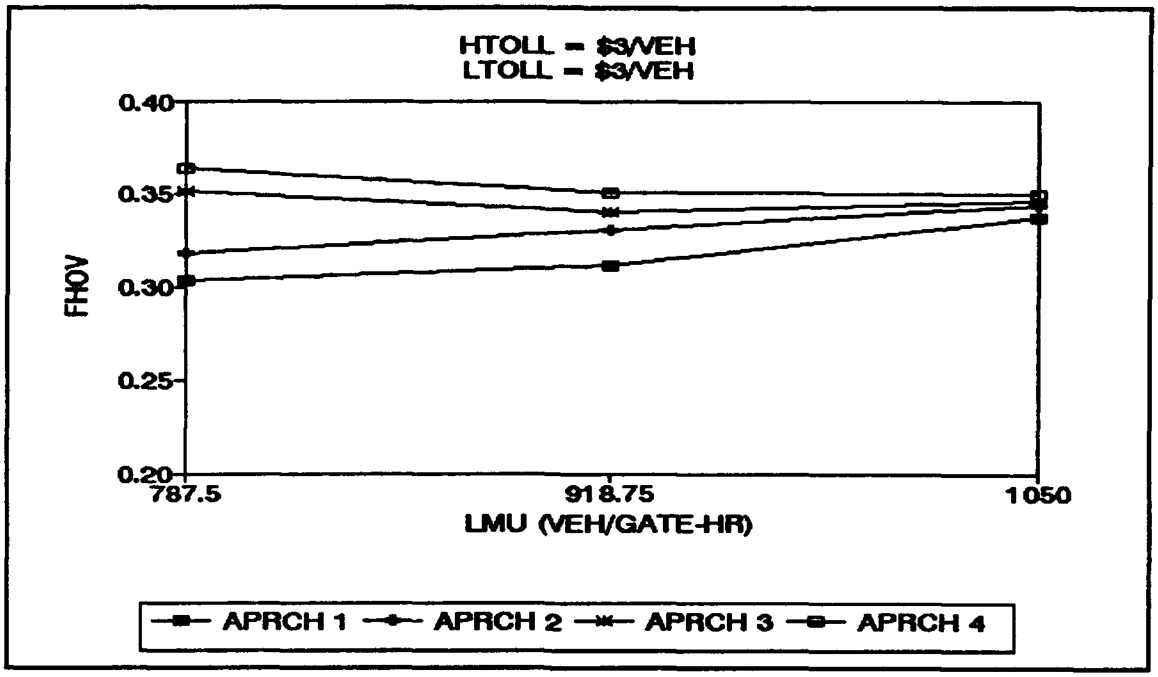

Figure 20 - Strategy 7

more correctly model the behavior of the real system. This will be discussed in the next chapter, Discussions and Conclusion.

CHAPTER 4 DISCUSSIONS AND CONCLUSION

In the last chapter, the sensitivity of the fraction of total trip makers that use HOVs (FHOV) to seven different strategies was presented. This chapter discusses those results as well as the impact of the policies on the number of vehicles which use the facility and the number of persons that can be moved. Conclusions which can be drawn from implementing the various strategies are also discussed.

4.1 Discussion of Results

For the DYNAMO model constructed for Approach 1, the wait time for HOVs and LOVs (HWT and LWT) was ignored and assumed to be zero in both cases. The impact of ignoring wait time was significant. In this model, travel time was estimated by first determining the downstream volume. Using a speed-volume relationship, the downstream volume was used to calculate a travel speed, which was then used to calculate a travel time. A discussion of the results of this approach follows.

Raising the LOV cost of the toll (Strategy 1) had the expected outcome of increasing the fraction of total trip makers utilizing HOVs (FHOV). As LOV trip makers seek to reduce their total cost, or disutility, they will shift to HOVs in an attempt to reduce their costs by spreading their cost over the additional persons in a vehicle.

The affect on FHOV as a result of implementing Strategy 2 (increasing the HOV toll cost) is also as expected. Since

trip makers are seeking to reduce their costs, an increase in the HOV toll would have the tendency to influence them away from that mode of travel.

Strategy 3, which is a combination of the first two strategies, effects the value for FHOV but more than might have been expected. When Strategies 1 and 2 are combined, it would be reasonable to assume there would be a cancelling effect, with the value for FHOV increasing but to a level much less than if Strategy 1 was implemented alone. However, the increase in the HOV toll cost has less impact on the value for FHOV when combined with a corresponding increase in the LOV toll cost than when the HOV toll cost is increased alone.

The effect on the value for FHOV as a result of implementing Strategy 4 (decreasing the LOV toll gate service rate while HTOLL and LTOLL remain at $0 per vehicle) is not as expected. It would be reasonable to assume when the value for the LOV toll gate service rate (LMU) is decreased, the wait time associated with receiving service (i.e., passing through the toll facility) should increase for LOVs. This increase in the expected wait time should result in a greater portion of trip makers utilizing HOVs in an effort to reduce their wait time and, hence, their disutility. In this model, just the opposite occurred. As LMU is decreased there is a decrease in the number of trip makers using HOVs. The behavior of this model, although not what we would expect in a real system, can be understood when we realize wait time is not a factor in

calculating FHOV for this approach. The result of the decreased LOV toll gate service rate serves to decrease downstream LOV demand, which in turn allows a greater travel speed and lower travel time, leading to less cost to the LOV trip maker in terms of the time it takes to make the trip. The model formulation accounts only for this reduced travel time and hence, allows for more LOVs to use the faster mode rather than increasing the number of HOVs in a effort to reduce disutility.

As discussed above, decreasing the LOV toll gate service rate should result in an increase in the value for the fraction of total trip makers that utilize HOVs. Since Strategies 5, 6 and 7 correspond to Strategies 1, 2 and 3, respectively, with the additional factor of decreasing the LOV toll gate service rate (LMU), it would be reasonable to assume the values obtained for FHOV when Strategies 5, 6 and 7 are implemented would be greater than those obtained in Strategies 1, 2 and 3. In other words, the number of trip makers using HOVs should increase to a greater extent as a result of implementing Strategy 5 as compared to implementing Strategy 1, Strategy 6 as compared to Strategy 2 and Strategy 7 to Strategy 3. Reviewing the figures presented in Table C, one can see this is not the case. In each instance, the values obtained for FHOV when Strategies 5, 6 and 7 are implemented are less than those obtained when Strategies 1, 2 and 3 are implemented. Once again, this is a result of not taking into

consideration the increased wait time that can be expected when the LOV toll gate service rate in decreased. Not only has the cost of making the trip increased through the increase in tolls as in Strategies 1, 2 and 3, but wait time also increases when the last three strategies are implemented. As a consequence of the increased wait time, the cost experienced by LOVs should also increase. Instead of the increased wait time influencing trip makers to use HOVs, trip makers see only the decreased travel time as a result of less downstream demand. Therefore, less trip makers choose to use HOVs.

It should be apparent, that although the model used in Approach 1 has been verified to operate as designed, it should not be considered a valid model structure since it does not appear to accurately predict the general impact on the values of FHOV as each strategy is implemented. This is a result of the model not taking into consideration the wait time experienced by the trip makers, particularly LOV trip makers.

As in Approach 1, the model for Approach 2 was constructed ignoring the wait time for HOVs and LOVs (HWT and LWT). Wait time was assumed to be zero in both cases. Travel time was estimated using a demand-capacity ratio model. Generally speaking, the behavior of this model is very similar to that of the model used in Approach 1.

Although the actual numbers are different, implementing the first three strategies in Approach 2 have the same basic impact on the values for FHOV as in Approach 1 and for the

same reasons. See Table D. The difference in the values is a result of using a different model structure. The impacts of the remaining strategies (Strategies 4 through 7) on the value for FHOV are also much the same as that in Approach 1.

The model used in Approach 2 operates as designed. However, as with Approach 1, it does not appear to be a valid representation of the system. The results of these two approaches would indicate that vehicle (HOV and LOV) wait time is a significant factor and must be taken into account.

Approach 3 implemented the same method used in Approach 1 to calculate travel time. Rather than assume the wait time for HOVs and LOVs to be zero, a cumulative demand and cumulative capacity model is implemented to account for the wait time. This approach is a more accurate representation of the dynamics of a real system. Reference Table E.

Implementing Strategies 1, 2 and 3 (increasing HOV toll cost, increasing LOV toll cost, increasing both HOV and LOV toll costs together) resulted in the expected changes to the value of FHOV. Since wait time is considered in this approach, the impact on the value for FHOV when Strategy 4 (decreasing the toll gate service rate) is implemented results in a modest increase verses a decrease in value of FHOV for the first two approaches. When Strategies 5, 6 and 7 are implemented, the value for FHOV is greater than the value obtained when the corresponding Strategies 1, 2 and 3 are implemented. The response of the model used in this approach

is similar to what might be expected in a real system of this nature. With the exception of Strategy 2, the implemented strategy results in a greater disutility for LOVs. As a result, a portion of the LOVs trip makers will seek to reduce their disutility and convert to the HOV mode of travel, which should lead to an increase in the number of HOVs. Strategy 2, on the other hand, increases the disutility experienced by HOV trip makers and one could reasonably expect a decrease in the value of FHOV as predicted by this approach.

Finally, Approach 4 uses the speed-volume relationship to calculate travel time as in Approaches 1 and 3. Wait time for HOVs and LOVs (HWT and LWT) is estimated using an enhanced cumulative demand and capacity model. Approach 4 would also seem to be a more realistic representation of the response of a real system. Based on the figures presented in Table F, this approach is less sensitive than Approach 3 to an increase in toll costs for both HOVs and LOVs while it is more sensitive to a decrease in the toll gate service rate. This increased sensitivity might be explained when we consider the model used to estimate the wait time. For the same conditions, the result of implementing the enhanced cumulative demand and cumulative capacity method will be a greater estimated wait time than the method used in Approach 3. Since decreasing the toll gate service rate has the effect of increasing the wait time experienced by LOVs, the enhanced approach estimates a larger value for wait time and,

therefore, a greater disutility is experienced by LOVs which in turn leads to a larger value for FHOV.

Based on the results of the sensitivity analyses of Chapter 3 and the discussion so far, it is reasonable to conclude Approaches 1 and 2 are not valid models for the system depicted in this project. These approaches do not take into consideration the wait time experienced by trip makers. Wait time, however, has a significant impact on a trip makers choice of travel mode. In addition, if the models used in Approaches 1 and 2 would were used as tools to evaluate possible strategies to influence trip makers to use HOVs, the results would lead to incorrect conclusions concerning the effects of those policies as demonstrated in Chapter 3.

4.2 TSM Strategy Evaluation

The second purpose of this project was to use a model that was determined to be a valid representation of the highway facility to explore the impacts of the different strategies on the twin goals of TSM: reducing the vehicles using the facility while increasing the number of persons moved. Approaches 3 and 4 will be used to evaluate the strategies and their effect on the number of vehicles and the number of persons moved.

Thus far in the discussion and analysis of the four approaches, the focus has been on the impact of the various strategies on the fraction of total trip makers that use HOVs (FHOV). Attempting to maximize the value of FHOV does not

necessarily mean the goals of reducing the number of vehicles on the facility and increasing the number of persons moved will be achieved.

Consider Table G which shows for Approach 3 the impact each of the seven strategies has on the fraction of total trip makers that utilize HOV (FHOV), the total vehicles using the facility and the total persons moved through the facility as compared to the base strategy. The values for Total Vehicles and Total Persons were arrived at in the following manner. (This discussion also applies to the values obtained for Approach 4.)

Table G - Total Vehicles and Persons (Approach 3)

Strategy	FHOV	Total Vehicles	Total Persons
Base	.2967	7,338	9,415
1	.3630	7,571	10,112
2	.2655	7,229	9,088
3	.3459	7,511	9,932
4	.3080	5,803	7,959
5	.3668	6,013	8,576
6	.2803	5,706	7,668
7	.3515	5,955	8,414

In Approaches 3 and 4, the downstream demand is limited by the toll gate service rate. Since the number of vehicles attempting to use the LOV lanes is greater than the combined total of the toll gate service rate in each strategy, the

number of vehicles, and thus persons (the average vehicle occupancy for LOVs is 1 person per vehicle), able to use the LOV lanes on a per hour basis is 6300 for the Base Strategy and Strategies 1, 2 and 3. In the last four strategies, the number of LOVs and persons able to use the LOV lanes per hour is 4725. The number of persons per hour using HOVs is found by multiplying the value for FHOV by the peak demand of 10,500 person-trips. The number of HOVs is determined by dividing the persons using HOVs by 3 since the HOV average vehicle occupancy is 3 persons per vehicle. The values for persons and vehicles are then added together to find the values presented in Tables G and H.

Table H - Total Vehicles and Persons (Approach 4)

Strategy	FHOV	Total Vehicles	Total Persons
Base	.3092	7,382	9,547
1	.3649	7,577	10,131
2	.2854	7,299	9,297
3	.3498	7,524	9,973
4	.3334	5,892	8,226
5	.3753	6,039	8,666
6	.3144	5,825	8,026
7	.3642	6,000	8,549

If the goal had been to maximize the number of HOVs that utilize the toll facility, Strategy 5 (raising the LOV toll cost and decreasing the LOV toll gate service rate) would be

implemented based on the data discussed so far. However, in order to maximize the number of persons moved through the facility, increasing the LOV toll cost alone (Strategy 1) should be implemented as shown in Table G. On the other hand, in order to minimize the number of vehicles using the facility, Strategy 6, increasing the toll cost to both HOVs and LOVs as well as decreasing the LOV toll gate service rate, should be implemented. The same conclusions regarding Strategy 5 can be made for Approach 4 based on the data in Table H.

4.3 Project Conclusions

Based on the results of this project, the time trip makers spend waiting is an important factor in an attempt to determine what fraction of total trip makers utilize HOVs. As wait time is increased for one mode of transportation over another, it is reasonable to expect a decrease in the number of trip makers using that mode coupled with a corresponding increase in the number of trip makers using the alternate mode.

In Approaches 1 and 2, wait time was not taken into consideration and assumed to be zero. As a result, when wait time is increased for LOVs through decreasing the toll gate service rate (Strategy 4), the fraction of total trip makers that utilize HOVs actually decreased verses increasing as expected when compared to the base strategy. When Strategies 5, 6 and 7 are implemented, the values obtained for FHOV were

less than expected when compared to the values obtained when Strategies 1, 2 and 3 were implemented.

It is safe to conclude the changes in the fraction of total trip makers that utilize HOVs in these approaches are the results of changes to the travel time experienced by the trip makers and is in no way affected by wait time. When Strategies 4 through 7 are implemented, LOV trip makers see a reduced travel time due to a decrease in LOV downstream demand. This reduced travel time serves to influence more trip makers to utilize LOVs rather than increasing the use of HOVs.

Approaches 1 and 2 show policy sensitivity, or policy reversal, when compared to Approaches 3 and 4. Based on the results of implementing Strategies 4 through 7 in Approaches 1 or 2, the conclusion could be made that in order to influence more trip makers to utilize HOVs, a higher value for the LOV toll gate service rate would be more beneficial since decreasing the toll gate service rate decreases FHOV. However, implementing and examining this strategy in Approach 3 or 4 would lead to the opposite conclusion: a lower value for the LOV toll gate service rate would be more beneficial since decreasing the toll gate service rate increases the value of FHOV.

Based on the above discussions, it is reasonable to conclude Approaches 1 and 2 are not adequate approaches based on 1.) their incorrect response as compared to the reasonable

and expected behavior of a real system and 2.) the fact they would lead to incorrect conclusions regarding a strategy that decreases the LOV toll gate service rate. Furthermore, wait time is a factor which must be included if a model is to correctly represent a real system of this nature.

Wait time is taken into consideration in Approaches 3 and 4. Both of these approaches more closely represent the expected, general response of a real system although the sensitivity of each model differs from one another. For example, Approach 3 would appear to be more sensitive to increases in the cost of the toll for either or both HOVs and LOVs while Approach 4 appears to be more sensitive to factors that impact wait time when Strategies 4 and 6 are implemented. From the results of this project, perhaps the only conclusion that can be drawn concerning these two approaches is they both respond as a real system might generally be expected to respond; an increase in toll cost or a decrease in the LOV toll gate service rate will increase the fraction of total trip makers that utilize HOVs.

Using the results of Approaches 3 and 4, it was shown that an increase in the LOV toll cost (Strategy 1) is effective in increasing the number of people moved through the facility while an increase in toll costs for all vehicles as well as reducing the LOV toll gate service rate (Strategy 6) reduces the number of vehicles using the facility. Although neither of these strategies maximized the value of the

fraction of total trip makers that will utilize HOVs, in both approaches, the strategies achieved one aspect of improved efficiency. Another measurement is needed to determine which of these two strategies should be implemented, such as the comparison of amount of disutility experienced by the different modes of travel.

A final, and perhaps secondary conclusion, may be made based on the results of the numerical sensitivity analysis performed earlier. In Chapter 3, the sensitivity of each approach to the factors for the cost of time (CTIME) and average vehicle occupancy for HOVs and LOVs (HAVO and LAVO) was examined and presented in Figures 11, 12 and 13. Each approach appeared to be rather insensitive to changes in the estimated cost of time (CTIME) and the HOV average vehicle occupancy (HAVO) as shown in Figures 11 and 12. All four approaches display significant sensitivity to the value of LOV average vehicle occupancy (LAVO) as can be seen in Figure 13, particularly Approaches 3 and 4. Although the value for LAVO was assumed to be one (1) in each approach for this project, the value for this parameter would need to be estimated with more precision as compared to the values for the cost of time and the average vehicle occupancy for HOVs in order to accurately study the effects of implementing different strategies in a real system.

CHAPTER 5 FINAL SUMMARY AND RECOMMENDATIONS

This chapter will summarize the results of this project with respect to the original objectives. In addition, some suggestions for additional research are made.

5.1 Summary of Conclusions and Observations

There are three basic conclusions and a general observation that can be made based on the results of the different approaches. The first conclusion is that in this type of system, wait time is an integral factor and must be taken into consideration. When wait time is not considered, as in Approaches 1 and 2, the final results are based solely on travel time, which does not accurately represent the dynamics of the system. Second, based on the results of Approaches 3 and 4, increasing the HOV and LOV cost of tolls and decreasing the LOV toll gate service rate serve as effective strategies to increase the fraction of total trip makers that utilize HOVs. Increasing the LOV toll cost in combination with decreasing the LOV toll gate service rate serve to maximize the number of trip makers that utilize HOVs. Finally, although increasing the LOV toll cost and decreasing the LOV toll gate service rate maximizes the value for FHOV, it does not attain the attain the goals of TSM. No single strategy achieves both goals simultaneously. An increase in the LOV toll cost maiximizes the number of persons that can be moved through the facility while increasing costs to both

types of vehicles coupled with a decrease.

An observation is made that in each approach, particularly in Approaches 3 and 4, the models were more sensitive to changes in the value for LOV average vehicle occupancy than to any other parameter. When compared to the parameter for the cost of time and HOV average vehicle occupancy, the value for LOV average vehicle occupancy would need to be more carefully estimated. In addition, in order to prevent an overly optimistic conclusion, it might be better to estimate the LOV average vehicle occupancy on the high side of it's true value.

5.2 Recommendations for Further Research

The purpose of this project has been to investigate different approaches to modeling a hypothetical highway facility and to examine the transportation system management strategies of road pricing, metering and the priority treatment of HOVs on the fraction of total trip makers that utilize HOVs. For this project, the facility has been greatly simplified, isolating the facility from the remainder of the road network and ignoring the societal impacts of various policy implementations. In addition, an assumption was made to use a rather simple behavioral modal split model.

In light of these simplifications, perhaps a more comprehensive model could be developed to measure societal response to the implementation of various policies. Societal responses might be measured subjectively in terms of user

satisfaction or perceived value as compared to total trip cost.

Rather than isolating the toll facility from the road network, perhaps factors which account for optional routes available to trip makers might be incorporated. The addition of interchanges along the toll facility as well a model to account for the road network feeding the toll facility may also be included.

Various modal split models could also be examined. For this model, one specific form of a behavioral model was used for the modal split in all cases. Other forms of behavior models could be used as well as other modal split models including those based on regression analysis and empirical studies.

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APPENDIX A - Basic DYNAMO Program

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* BASIC DYNAMO PROGRAM
NOTE ************ SYSTEM VARIABLES ***************************
C DEMAND=10500      DEMAND - PEAK DEMAND (PER-TRIPS/HR)
C DUR=1             DUR - DURATION OF CONGESTION (HR)
C DFSPD=70          DFSPD - DOWNSTREAM FREE SPEED (MI/HR)
C DCAP=2100         DCAP - DOWNSTREAM CAPACITY (VEH/LANE-HR)
C DJAMK=120        DJAMK - DOWNSTREAM JAM DENSITY (VEH/LANE-MI)
C HLANES=1          HLANES - HOV LANES (LANE)
C LLANES=3          LLANES - LOV LANES (LANE)
C LEN=15            LEN - TOLL FACILITY LENGTH (MI)
C HAVO=3            HAVO - HOV AVE VEH OCCUPANCY (PER/VEH)
C LAVO=1            LAVO - LOV AVE VEH OCCUPANCY (PER/VEH)
C CTIME=8           CTIME - COST OF TIME ($/PER-HR)
C FHOVM=.4          FHOVM - FRACTION HOV MAX (DIM)
C FHOVN=0           FHOVN - FRACTION HOV NORMAL (DIM)
NOTE ************ DECISION VARIABLES *************************
C HMU=              HMU - HOV TOLL GATE SER RATE (VEH/GATE-HR)
C LMU=              LMU - LOV TOLL GATE SER RATE (VEH/GATE-HR)
C HTOLL=            HTOLL - HOV TOLL COST ($/VEH)
C LTOLL=            LTOLL - HOV TOLL COST ($/VEH)
NOTE ************ HOV SEGMENT ********************************
NOTE ------------ HOV TRIPS AND NUMBER OF HOVS --------------
A HTRIPS.K=FHOV.K*DEMAND
NOTE                HTRIPS - HOV TRIPS (PER-TRIPS/HR)
A NHOV.K=HTRIPS.K/HAVO
NOTE                NHOV - NUMBER OF HOVS (VEH/HR)
NOTE ------------ HOV WAIT TIME -----------------------------
A HWT.K=
NOTE                HWT - HOV WAIT TIME (HR)
NOTE ------------ HOV TRAVEL TIME ---------------------------
A HTT.K=
NOTE                HTT - HOV TRAVEL TIME (HR)
NOTE ------------ HOV TOTAL TRIP TIME -----------------------
A HTTT.K=HWT.K+HTT.K
NOTE                HTTT - HOV TOTAL TRIP TIME
NOTE ************ LOV SEGMENT ********************************
NOTE ------------ LOV TRIPS AND NUMBER OF LOVS --------------
A LTRIPS.K=(1-FHOV.K)*DEMAND
NOTE                LTRIPS - LOV TRIPS (PER-TRIPS/HR)
A NLOV.K=LTRIPS.K/LAVO
NOTE                NLOV - NUMBER OF LOVS (VEH/HR)
NOTE ------------ LOV WAIT TIME -----------------------------
A LWT.K=
NOTE                LWT - LOV WAIT TIME (HR)
NOTE ------------ LOV TRAVEL TIME ---------------------------
A LTT.K=
NOTE                LTT - LOV TRAVEL TIME (HR)
```

```
NOTE ------------ LOV TOTAL TRIP TIME -----------------------
A LTTT.K=LWT.K+LTT.K
NOTE                 LTTT - LOV TOTAL TRIP TIME
NOTE ************ DISUTILITY SEGMENT *************************
A ZHOV.K=CTIME*HTTT.K+HTOLL/HAVO
NOTE                 ZHOV - HOV DISUTILITY ($/PER)
A ZLOV.K=CTIME*LTTT.K+LTOLL/LAVO
NOTE                 ZLOV - LOV DISUTILITY ($/PER)
A DELTAZ.K=ZHOV.K-ZLOV.K
NOTE                 DELTAZ - DIFFERENCE IN DISUTILITY ($/PER)
NOTE ************ MODAL SPLIT SEGMENT ************************
L FHOV.K=FHOVM/(1+EXP(DELTAZ.J/2))
N FHOV=FHOVN
NOTE                 FHOV - FRACTION OF TOTAL TRIPS HOV (DIM)
NOTE ************ SPECIFICATION SEGMENT **********************
SPEC DT=.25,LENGTH=4,PRTPER=.25
PRINT FHOV,HQ,LQ
```

APPENDIX B - Speed-Volume Model

```
* APPROACH #1 (SPEED-VOLUME MODEL)
NOTE ************ SYSTEM VARIABLES *****************************
C DEMAND=10500      DEMAND - PEAK DEMAND (PER-TRIPS/HR)
C FFSPD=70          FFSPD - FREE FLOW SPEED (MI/HR)
C DJAMK=120        DJAMK - DOWNSTREAM JAM DENSITY (VEH/LANE-MI)
C HLANES=1          HLANES - HOV LANES (LANE)
C LLANES=3          LLANES - LOV LANES (LANE)
C LEN=15            LEN - TOLL FACILITY LENGTH (MI)
C HAVO=3            HAVO - HOV AVE VEH OCCUPANCY (PER/VEH)
C LAVO=1            LAVO - LOV AVE VEH OCCUPANCY (PER/VEH)
C CTIME=8           CTIME - COST OF TIME ($/PER-HR)
C FHOVM=.4          FHOVM - FRACTION HOV MAX (DIM)
C FHOVN=0           FHOVN - FRACTION HOV NORMAL (DIM)
NOTE ************ DECISION VARIABLES *************************
C HMU=              HMU - HOV TOLL GATE SER RATE (VEH/GATE-HR)
C LMU=              LMU - LOV TOLL GATE SER RATE (VEH/GATE-HR)
C HTOLL=            HTOLL - HOV TOLL COST ($/VEH)
C LTOLL=            LTOLL - HOV TOLL COST ($/VEH)
NOTE ************ HOV SEGMENT **********************************
NOTE ------------ HOV TRIPS AND NUMBER OF HOVS ---------------
A HTRIPS.K=FHOV.K*DEMAND
NOTE                HTRIPS - HOV TRIPS (PER-TRIPS/HR)
A NHOV.K=HTRIPS.K/HAVO
NOTE                NHOV - NUMBER OF HOVS (VEH/HR)
NOTE ------------ HOV WAIT TIME ------------------------------
A HTGSR.K=HMU*2
NOTE               HTGSR - HOV TOLL GATE SER RATE (VEH/LANE-HR)
A HWT.K=0
NOTE                HWT - HOV WAIT TIME (HR)
NOTE ------------ HOV TRAVEL TIME ----------------------------
A HQ.K=MIN(NHOV.K/HLANES,HTGSR.K)
NOTE                HQ - HOV DOWNSTREAM VOLUME (VEH/LANE-HR)
N JDOFS=DJAMK/FFSPD
NOTE                JDOFS - JAM DENSITY OVER FREE FLOW SPEED
A HSPD.K=(DJAMK+SQRT(DJAMK**2-4*JDOFS*HQ.K))/(2*JDOFS)
NOTE                HSPD - HOV SPEED (MI/HR)
A HTT.K=LEN/HSPD.K
NOTE                HTT - HOV TRAVEL TIME (HR)
NOTE ------------ HOV TOTAL TRIP TIME ------------------------
A HTTT.K=HWT.K+HTT.K
NOTE                HTTT - HOV TOTAL TRIP TIME
NOTE ************ LOV SEGMENT **********************************
NOTE ------------ LOV TRIPS AND NUMBER OF LOVS ---------------
A LTRIPS.K=(1-FHOV.K)*DEMAND
NOTE                LTRIPS - LOV TRIPS (PER-TRIPS/HR)
A NLOV.K=LTRIPS.K/LAVO
NOTE                NLOV - NUMBER OF LOVS (VEH/HR)
```

```
NOTE ------------ LOV WAIT TIME ------------------------------
A LTGSR.K=LMU*2
NOTE              LTGSR - LOV TOLL GATE SER RATE (VEH/LANE-HR)
A LWT.K=0
NOTE                LWT - LOV WAIT TIME (HR)
NOTE ------------ LOV TRAVEL TIME ----------------------------
A LQ.K=MIN(NLOV.K/LLANES,LTGSR.K)
NOTE                LQ - LOV DOWNSTREAM VOLUME (VEH/LANE-HR)
A LSPD.K=(DJAMK+SQRT(DJAMK**2-4*JDOFS*LQ.K))/(2*JDOFS)
NOTE                LSPD - LOV SPEED (MI/HR)
A LTT.K=LEN/LSPD.K
NOTE                LTT - LOV TRAVEL TIME (HR)
NOTE ------------ LOV TOTAL TRIP TIME ------------------------
A LTTT.K=LWT.K+LTT.K
NOTE                LTTT - LOV TOTAL TRIP TIME
NOTE ************ DISUTILITY SEGMENT **************************
A ZHOV.K=CTIME*HTTT.K+HTOLL/HAVO
NOTE                ZHOV - HOV DISUTILITY ($/PER)
A ZLOV.K=CTIME*LTTT.K+LTOLL/LAVO
NOTE                ZLOV - LOV DISUTILITY ($/PER)
A DELTAZ.K=ZHOV.K-ZLOV.K
NOTE                DELTAZ - DIFFERENCE IN DISUTILITY ($/PER)
NOTE ************ MODAL SPLIT SEGMENT *************************
L FHOV.K=FHOVM/(1+EXP(DELTAZ.J/2))
N FHOV=FHOVN
NOTE                FHOV - FRACTION OF TOTAL TRIPS HOV (DIM)
NOTE ************ SPECIFICATION SEGMENT ***********************
SPEC DT=.25,LENGTH=4,PRTPER=.25
PRINT FHOV,HQ,LQ
```

APPENDIX C - Demand-Capacity Ratio Model

```
* APPROACH #2 (DEMAND-CAPACITY RATION MODEL)
NOTE ************ SYSTEM VARIABLES ****************************
C DEMAND=10500     DEMAND - PEAK DEMAND (PER-TRIPS/HR)
C FFSPD=70         FFSPD - FREE FLOW SPEED (MI/HR)
C DCAP=2100        DCAP - DOWNSTREAM CAPACITY (VEH/LANE-HR)
C HLANES=1         HLANES - HOV LANES (LANE)
C LLANES=3         LLANES - LOV LANES (LANE)
C LEN=15           LEN - TOLL FACILITY LENGTH (MI)
C HAVO=3           HAVO - HOV AVE VEH OCCUPANCY (PER/VEH)
C LAVO=1           LAVO - LOV AVE VEH OCCUPANCY (PER/VEH)
C CTIME=8          CTIME - COST OF TIME ($/PER-HR)
C FHOVM=.4         FHOVM - FRACTION HOV MAX (DIM)
C FHOVN=0          FHOVN - FRACTION HOV NORMAL (DIM)
NOTE ************ DECISION VARIABLES **************************
C HMU=1050         HMU - HOV TOLL GATE SER RATE (VEH/GATE-HR)
C LMU=1050         LMU - LOV TOLL GATE SER RATE (VEH/GATE-HR)
C HTOLL=1          HTOLL - HOV TOLL COST ($/VEH)
C LTOLL=1          LTOLL - HOV TOLL COST ($/VEH)
NOTE ************ HOV SEGMENT *********************************
NOTE ------------ HOV TRIPS AND NUMBER OF HOVS ---------------
A HTRIPS.K=FHOV.K*DEMAND
NOTE               HTRIPS - HOV TRIPS (PER-TRIPS/HR)
A NHOV.K=HTRIPS.K/HAVO
NOTE               NHOV - NUMBER OF HOVS (VEH/HR)
NOTE ------------ HOV WAIT TIME -------------------------------
A HTGSR.K=HMU*2
NOTE              HTGSR - HOV TOLL GATE SER RATE (VEH/LANE-HR)
A HWT.K=0
NOTE               HWT - HOV WAIT TIME (HR)
NOTE ------------ HOV TRAVEL TIME -----------------------------
A HQ.K=MIN(NHOV.K/HLANES,HTGSR.K)
NOTE               HQ - HOV DOWNSTREAM VOLUME (VEH/LANE-HR)
A HDCR.K=HQ.K/DCAP
NOTE               HDCR - HOV DEMAND-CAPACITY RATIO (DIM)
A HTT.K=EXP(HDCR.K)*(LEN/FFSPD)
NOTE               HTT - HOV TRAVEL TIME (HR)
NOTE ------------ HOV TOTAL TRIP TIME -------------------------
A HTTT.K=HWT.K+HTT.K
NOTE               HTTT - HOV TOTAL TRIP TIME
NOTE ************ LOV SEGMENT *********************************
NOTE ------------ LOV TRIPS AND NUMBER OF LOVS ---------------
A LTRIPS.K=(1-FHOV.K)*DEMAND
NOTE               LTRIPS - LOV TRIPS (PER-TRIPS/HR)
A NLOV.K=LTRIPS.K/LAVO
NOTE               NLOV - NUMBER OF LOVS (VEH/HR)
```

```
NOTE ------------ LOV WAIT TIME -----------------------------
A LTGSR.K=LMU*2
NOTE              LTGSR - LOV TOLL GATE SER RATE (VEH/LANE-HR)
A LWT.K=0
NOTE                LWT - LOV WAIT TIME (HR)
NOTE ------------ LOV TRAVEL TIME ---------------------------
A LQ.K=MIN(NLOV.K/LLANES,LTGSR.K)
NOTE                LQ - LOV DOWNSTREAM VOLUME (VEH/LANE-HR)
A LDCR.K=LQ.K/DCAP
NOTE                LDCR - LOV DEMAND-CAPACITY RATIO (DIM)
A LTT.K=EXP(LDCR.K)*(LEN/FFSPD)
NOTE                LTT - LOV TRAVEL TIME (HR)
NOTE ------------ LOV TOTAL TRIP TIME -----------------------
A LTTT.K=LWT.K+LTT.K
NOTE                LTTT - LOV TOTAL TRIP TIME
NOTE ************ DISUTILITY SEGMENT *************************
A ZHOV.K=CTIME*HTTT.K+HTOLL/HAVO
NOTE                ZHOV - HOV DISUTILITY ($/PER)
A ZLOV.K=CTIME*LTTT.K+LTOLL/LAVO
NOTE                ZLOV - LOV DISUTILITY ($/PER)
A DELTAZ.K=ZHOV.K-ZLOV.K
NOTE                DELTAZ - DIFFERENCE IN DISUTILITY ($/PER)
NOTE ************ MODAL SPLIT SEGMENT ************************
L FHOV.K=FHOVM/(1+EXP(DELTAZ.J/2))
N FHOV=FHOVN
NOTE                FHOV - FRACTION OF TOTAL TRIPS HOV (DIM)
NOTE ************ SPECIFICATION SEGMENT **********************
SPEC DT=.25,LENGTH=4,PRTPER=.25
PRINT FHOV,HQ,LQ
```

APPENDIX D - Cumulative Demand/Capacity Model

```
* APPROACH #3 (SPEED-VOLUME, CUM DEMAND/CUM CAPACITY MODEL)
NOTE ************ SYSTEM VARIABLES *****************************
C DEMAND=10500      DEMAND - PEAK DEMAND (PER-TRIPS/HR)
C DUR=1             DUR - DURATION OF EXCESS DEMAND (HR)
C FFSPD=70          FFSPD - FREE FLOW SPEED (MI/HR)
C DJAMK=120        DJAMK - DOWNSTREAM JAM DENSITY (VEH/LANE-MI)
C HLANES=1          HLANES - HOV LANES (LANE)
C LLANES=3          LLANES - LOV LANES (LANE)
C LEN=15            LEN - TOLL FACILITY LENGTH (MI)
C HAVO=3            HAVO - HOV AVE VEH OCCUPANCY (PER/VEH)
C LAVO=1            LAVO - LOV AVE VEH OCCUPANCY (PER/VEH)
C CTIME=8           CTIME - COST OF TIME ($/PER-HR)
C FHOVM=.4          FHOVM - FRACTION HOV MAX (DIM)
C FHOVN=0           FHOVN - FRACTION HOV NORMAL (DIM)
NOTE ************ DECISION VARIABLES *************************
C HMU=1050          HMU - HOV TOLL GATE SER RATE (VEH/GATE-HR)
C LMU=1050          LMU - LOV TOLL GATE SER RATE (VEH/GATE-HR)
C HTOLL=1           HTOLL - HOV TOLL COST ($/VEH)
C LTOLL=1           LTOLL - HOV TOLL COST ($/VEH)
NOTE ************ HOV SEGMENT **********************************
NOTE ------------ HOV TRIPS AND NUMBER OF HOVS --------------
A HTRIPS.K=FHOV.K*DEMAND
NOTE                HTRIPS - HOV TRIPS (PER-TRIPS/HR)
A NHOV.K=HTRIPS.K/HAVO
NOTE                NHOV - NUMBER OF HOVS (VEH/HR)
NOTE ------------ HOV WAIT TIME ------------------------------
A HTGSR.K=HMU*2
NOTE               HTGSR - HOV TOLL GATE SER RATE (VEH/LANE-HR)
A HDEL.K=DUR*((NHOV.K/HLANES)-HTGSR.K)
NOTE                HDEL - NUM FOR HOV AVE DELAY (VEH)
A HVEH.K=2*HTGSR.K
NOTE                HVEH - DENOM FOR HOV AVE DELAY (VEH/HR)
A HWT.K=MAX(HDEL.K/HVEH.K,0)
NOTE                HWT - HOV WAIT TIME (HR)
NOTE ------------ HOV TRAVEL TIME ----------------------------
A HQ.K=MIN(NHOV.K/HLANES,HTGSR.K)
NOTE                HQ - HOV DOWNSTREAM VOLUME (VEH/LANE-HR)
N JDOFS=DJAMK/FFSPD
NOTE                JDOFS - JAM DENSITY OVER FREE FLOW SPEED
A HSPD.K=(DJAMK+SQRT(DJAMK**2-4*JDOFS*HQ.K))/(2*JDOFS)
NOTE                HSPD - HOV SPEED (MI/HR)
A HTT.K=LEN/HSPD.K
NOTE                HTT - HOV TRAVEL TIME (HR)
NOTE ------------ HOV TOTAL TRIP TIME -----------------------
A HTTT.K=HWT.K+HTT.K
NOTE                HTTT - HOV TOTAL TRIP TIME
```

```
NOTE ************ LOV SEGMENT ***********************************
NOTE ------------ LOV TRIPS AND NUMBER OF LOVS ---------------
A LTRIPS.K=(1-FHOV.K)*DEMAND
NOTE                  LTRIPS - LOV TRIPS (PER-TRIPS/HR)
A NLOV.K=LTRIPS.K/LAVO
NOTE                  NLOV - NUMBER OF LOVS (VEH/HR)
NOTE ------------ LOV WAIT TIME ------------------------------
A LTGSR.K=LMU*2
NOTE                 LTGSR - LOV TOLL GATE SER RATE (VEH/LANE-HR)
A LDEL.K=DUR*((NLOV.K/LLANES)-LTGSR.K)
NOTE                  LDEL - NUM FOR LOV AVE DELAY (VEH)
A LVEH.K=2*LTGSR.K
NOTE                  LVEH - DENOM FOR LOV AVE DELAY (VEH/HR)
A LWT.K=MAX(LDEL.K/LVEH.K,0)
NOTE                  LWT - LOV WAIT TIME (HR)
NOTE ------------ LOV TRAVEL TIME ----------------------------
A LQ.K=MIN(NLOV.K/LLANES,LTGSR.K)
NOTE                  LQ - LOV DOWNSTREAM VOLUME (VEH/LANE-HR)
A LSPD.K=(DJAMK+SQRT(DJAMK**2-4*JDOFS*LQ.K))/(2*JDOFS)
NOTE                  LSPD - LOV SPEED (MI/HR)
A LTT.K=LEN/LSPD.K
NOTE                  LTT - LOV TRAVEL TIME (HR)
NOTE ------------ LOV TOTAL TRIP TIME -----------------------
A LTTT.K=LWT.K+LTT.K
NOTE                  LTTT - LOV TOTAL TRIP TIME
NOTE ************ DISUTILITY SEGMENT *************************
A ZHOV.K=CTIME*HTTT.K+HTOLL/HAVO
NOTE                  ZHOV - HOV DISUTILITY ($/PER)
A ZLOV.K=CTIME*LTTT.K+LTOLL/LAVO
NOTE                  ZLOV - LOV DISUTILITY ($/PER)
A DELTAZ.K=ZHOV.K-ZLOV.K
NOTE                  DELTAZ - DIFFERENCE IN DISUTILITY ($/PER)
NOTE ************ MODAL SPLIT SEGMENT ************************
L FHOV.K=FHOVM/(1+EXP(DELTAZ.J/2))
N FHOV=FHOVN
NOTE                  FHOV - FRACTION OF TOTAL TRIPS HOV (DIM)
NOTE ************ SPECIFICATION SEGMENT **********************
SPEC DT=.25,LENGTH=4,PRTPER=.25
PRINT FHOV,HQ,LQ
```

APPENDIX E - Enhanced Cumulative Demand/Capacity Model

```
* APPROACH #4 (SPEED-VOLUME, ENHANCED CUM DEM/CUM CAP MODEL)
NOTE ************ SYSTEM VARIABLES ****************************
C DEMAND=10500     DEMAND - PEAK DEMAND (PER-TRIPS/HR)
C DUR=1            DUR - DURATION OF EXCESS DEMAND (HR)
C UFSPD=93.334     UFSPD - UPSTREAM FREE SPEED (MI/HR)
C DFSPD=70         DFSPD - DOWNSTREAM FREE SPEED (MI/HR)
C JAMK=120         JAMK - JAM DENSITY (VEH/LANE-MI)
C HLANES=1         HLANES - HOV LANES (LANE)
C LLANES=3         LLANES - LOV LANES (LANE)
C LEN=15           LEN - TOLL FACILITY LENGTH (MI)
C HAVO=3           HAVO - HOV AVE VEH OCCUPANCY (PER/VEH)
C LAVO=1           LAVO - LOV AVE VEH OCCUPANCY (PER/VEH)
C CTIME=8          CTIME - COST OF TIME ($/PER-HR)
C FHOVM=.4         FHOVM - FRACTION HOV MAX (DIM)
C FHOVN=.2         FHOVN - FRACTION HOV NORMAL (DIM)
NOTE ************ DECISION VARIABLES **************************
C HMU=1050         HMU - HOV TOLL GATE SER RATE (VEH/GATE-HR)
C LMU=1050         LMU - LOV TOLL GATE SER RATE (VEH/GATE-HR)
C HTOLL=1          HTOLL - HOV TOLL COST ($/VEH)
C LTOLL=1          LTOLL - HOV TOLL COST ($/VEH)
NOTE ************ HOV SEGMENT **********************************
NOTE ------------ HOV TRIPS AND NUMBER OF HOVS --------------
A HTRIPS.K=FHOV.K*DEMAND
NOTE               HTRIPS - HOV TRIPS (PER-TRIPS/HR)
A NHOV.K=HTRIPS.K/HAVO
NOTE               NHOV - NUMBER OF HOVS (VEH/HR)
NOTE ------------ HOV WAIT TIME -----------------------------
A HTGSR.K=HMU*2
NOTE              HTGSR - HOV TOLL GATE SER RATE (VEH/LANE-HR)
A HQ1.K=MIN(NHOV.K/HLANES,2800)
NOTE               HQ1 - HOV UPSTREAM VOLUME (VEH/LANE-HR)
A HQ2.K=MIN(HQ1.K,HTGSR.K)
NOTE               HQ2 - HOV DOWNSTREAM VOLUME (VEH/LANE-HR)
A HK1R.K=UFSPD**2-4*(UFSPD/JAMK)*HQ1.K
NOTE              HK1R - PRODUCT FOR RADICAL IN NEXT EQUATION
A HK1.K=(UFSPD-SQRT(HK1R.K))/(2*(UFSPD/JAMK))
NOTE               HK1 - HOV UPSTREAM DENSITY (VEH/LANE-MI)
A HK4R.K=UFSPD**2-4*(UFSPD/JAMK)*HTGSR.K
NOTE              HK4R - PRODUCT FOR RADICAL IN NEXT EQUATION
A HK4.K=(UFSPD+SQRT(HK4R.K))/(2*(UFSPD/JAMK))
NOTE               HK4 - HOV QUEUE DENSITY (VEH/LANE-MI)
A HS.K=MAX(0,(HQ1.K-HQ2.K)/(HK4.K-HK1.K))
NOTE               HS - HOV QUEUE GROWTH RATE (MI/HR)
A HDEL.K=DUR*HK4.K*HS.K
NOTE               HDEL - NUM FOR HOV AVE DELAY (VEH)
A HVEH.K=2*HTGSR.K
NOTE               HVEH - DENOM FOR HOV AVE DELAY (VEH/HR)
A HWT.K=HDEL.K/HVEH.K
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NOTE                 HWT - HOV WAIT TIME (HR)
NOTE ------------ HOV TRAVEL TIME ----------------------------
A HSPDR.K=JAMK**2-4*(JAMK/DFSPD)*HQ2.K
NOTE               HSPDR - PRODUCT FOR RADICAL IN NEXT EQUATION
A HSPD.K=(JAMK+SQRT(HSPDR.K))/(2*(JAMK/DFSPD))
NOTE                 HSPD - HOV SPEED (MI/HR)
A HTT.K=LEN/HSPD.K
NOTE                 HTT - HOV TRAVEL TIME (HR)
NOTE ------------ HOV TOTAL TRIP TIME ------------------------
A HTTT.K=HWT.K+HTT.K
NOTE                 HTTT - HOV TOTAL TRIP TIME
NOTE ************ LOV SEGMENT *********************************
NOTE ------------ LOV TRIPS AND NUMBER OF LOVS ---------------
A LTRIPS.K=(1-FHOV.K)*DEMAND
NOTE                 LTRIPS - LOV TRIPS (PER-TRIPS/HR)
A NLOV.K=LTRIPS.K/LAVO
NOTE                 NLOV - NUMBER OF LOVS (VEH/HR)
NOTE ------------ LOV WAIT TIME ------------------------------
A LTGSR.K=LMU*2
NOTE               LTGSR - LOV TOLL GATE SER RATE (VEH/LANE-HR)
A LQ1.K=MIN(NLOV.K/LLANES,2800)
NOTE                 LQ1 - LOV UPSTREAM VOLUME (VEH/LANE-HR)
A LQ2.K=MIN(LQ1.K,LTGSR.K)
NOTE                 LQ2 - LOV DOWNSTREAM VOLUME (VEH/LANE-HR)
A LK1R.K=UFSPD**2-4*(UFSPD/JAMK)*LQ1.K
NOTE                LK1R - PRODUCT FOR RADICAL IN NEXT EQUATION
A LK1.K=(UFSPD-SQRT(LK1R.K))/(2*(UFSPD/JAMK))
NOTE                 LK1 - LOV UPSTREAM DENSITY (VEH/LANE-MI)
A LK4R.K=UFSPD**2-4*(UFSPD/JAMK)*LTGSR.K
NOTE                LK4R - PRODUCT FOR RADICAL IN NEXT EQUATION
A LK4.K=(UFSPD+SQRT(LK4R.K))/(2*(UFSPD/JAMK))
NOTE                 LK4 - LOV QUEUE DENSITY (VEH/LANE-MI)
A LS.K=MAX(0,(LQ1.K-LQ2.K)/(LK4.K-LK1.K))
NOTE                 LS - LOV QUEUE GROWTH RATE (MI/HR)
A LDEL.K=DUR*LK4.K*LS.K
NOTE                 LDEL - NUM FOR LOV AVE DELAY (VEH)
A LVEH.K=2*LTGSR.K
NOTE                 LVEH - DENOM FOR LOV AVE DELAY (VEH/HR)
A LWT.K=LDEL.K/LVEH.K
NOTE                 LWT - LOV WAIT TIME (HR)
NOTE ------------ LOV TRAVEL TIME ----------------------------
A LSPDR.K=JAMK**2-4*(JAMK/DFSPD)*LQ2.K
NOTE               LSPDR - PRODUCT FOR RADICAL IN NEXT EQUATION
A LSPD.K=(JAMK+SQRT(LSPDR.K))/(2*(JAMK/DFSPD))
NOTE                 LSPD - LOV SPEED (MI/HR)
A LTT.K=LEN/LSPD.K
NOTE                 LTT - LOV TRAVEL TIME (HR)
NOTE ------------ LOV TOTAL TRIP TIME ------------------------
A LTTT.K=LWT.K+LTT.K
NOTE                 LTTT - LOV TOTAL TRIP TIME
NOTE ************ DISUTILITY SEGMENT **************************
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```
A ZHOV.K=CTIME*HTTT.K+HTOLL/HAVO
NOTE                 ZHOV - HOV DISUTILITY ($/PER)
A ZLOV.K=CTIME*LTTT.K+LTOLL/LAVO
NOTE                 ZLOV - LOV DISUTILITY ($/PER)
A DELTAZ.K=ZHOV.K-ZLOV.K
NOTE                 DELTAZ - DIFFERENCE IN DISUTILITY ($/PER)
NOTE ************ MODAL SPLIT SEGMENT *************************
L FHOV.K=FHOVM/(1+EXP(DELTAZ.J/2))
N FHOV=FHOVN
NOTE                 FHOV - FRACTION OF TOTAL TRIPS HOV (DIM)
NOTE ************ SPECIFICATION SEGMENT **********************
SPEC DT=.25,LENGTH=4,PRTPER=.25
PRINT FHOV,HS,LS
```

END